Enabling Diverse Eye Anatomy Tracking

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Introduction

Approximately 42.5 million Americans live with some form of disability [2], with over 5 million of those living with some form of paralysis due to stroke, injury, or neurodegenerative disease [12].

- Large portion of this population still have control over their eyes
- Eyes convey attention, social and emotional information

Eye Tracking is a sensor technology that can detect a person's presence and follow what they are looking at in real-time

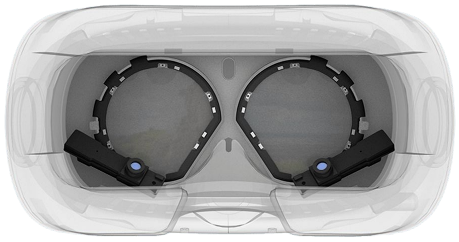

Fig 1. typical setup for eye tracking: HTC Vive Pro headset with Pupil Labs Eye trackers which consist of two infrared light sources and one camera per eye

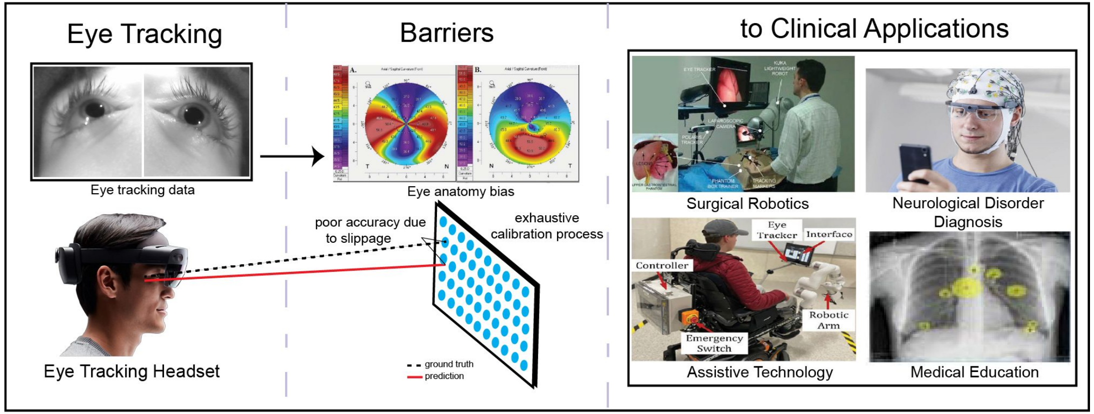

Fig 2. Eye tracking technologies can be implemented in several important clinical applications such as surgical robotics, neurological disorder diagnosis, assistive technologies for disabled individuals, and training medical students. However, the technology suffers from several barriers to clinical translation including poor gaze estimation accuracy due to head slippage, exhaustive calibration, and lack of robustness against diverse eye anatomy.

Introduction

What are some current problems in eye tracking?

- Human Physiology Bias
  - It was found that accuracy and precision for Asian participants was worse than that for African and Caucasian participants [14]
- Eye Anatomy Bias
  - Several popular model-based eye-tracking approaches assume population averages of particular eye parameters [15]
  - eye-health history including amblyopia (lazy eye), droopy eyelid, strabismus (crossed eye), astigmatism, and other characterizations of refractive errors
- Lack of Data
  - Capturing training data under various illumination conditions (over-exposure and hard shadows), occlusions (eyes lashes, blink, glasses frame), varying eye appearance (skin tone, make-up) is time-consuming and expensive

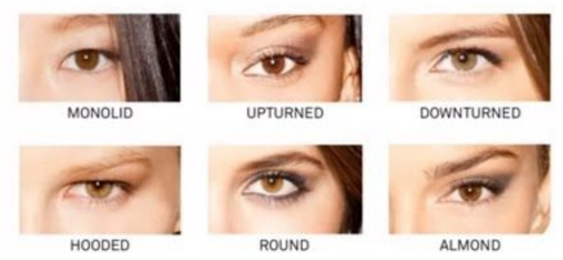

Fig 3. Different eye shapes showing diversity in human physiology

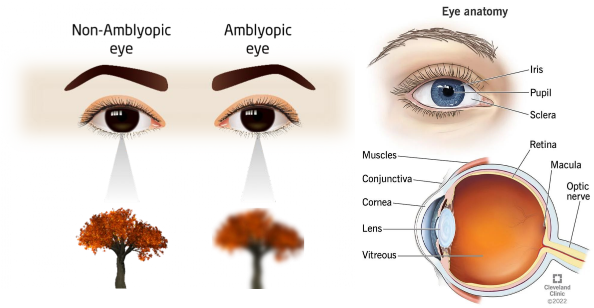

Fig 4. Lazy eye (left picture) and a diagram of anatomical eye features (right picture)

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Background

What have researchers done to address these issues?

Eye Rendering

- Adamo-Villani et al. (2005)
  - more realistic human eyes, concentrated on eyeball motion and pupil size change.
- Wood et al. (2015)
  - builds a collection of dynamic eye-region models from head scan geometry.
- Subsequent approaches have improved synthetic image quality by utilizing GANs or improved the eye model

- **Rendering** or image synthesis is the process of generating a photorealistic or non-photorealistic image from a 2D or 3D model by means of a computer

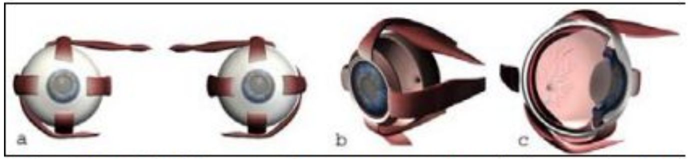

Fig 5. Model of the eyes. The two eyes and extrinsic muscles (a). model of the right eye without the sclera and cornea to reveal the internal structure of the eye (b) cross section of right eye (c) Adamo-Villani et al. (2005)

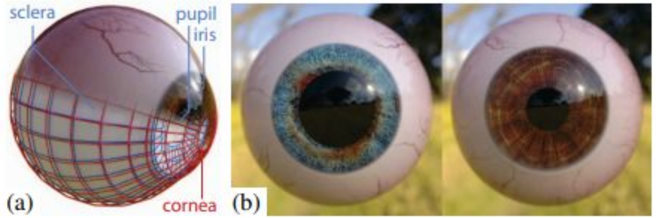

Fig 6. Eye model includes the sclera, pupil, iris, and cornea (a) and can exhibit realistic variation in both shape (pupillary dilation) and texture (iris color, scleral veins) (b) Wood et al. (2015)

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Hypothesis

What can be improved?

- anatomically accurate eye model
- domain gap between real and synthetic data

Hypothesis: eye tracking is a function of eye anatomy, using a more anatomically correct and more anatomically diverse eye model result in improved eye tracking performance.

Fig 8. Diverse eye anatomy

Key Terms

- **Iris**: The colored membrane around your pupil. It expands and contracts to control the amount of light that gets into your eye.
- **Pupil**: The round, dark central opening in your eye. This is where light comes in.
- **Cornea**: The clear front outer layer of your eye. It covers the iris.
- **Sclera**: The outer coat of the eyeball that forms the whites of your eyes.

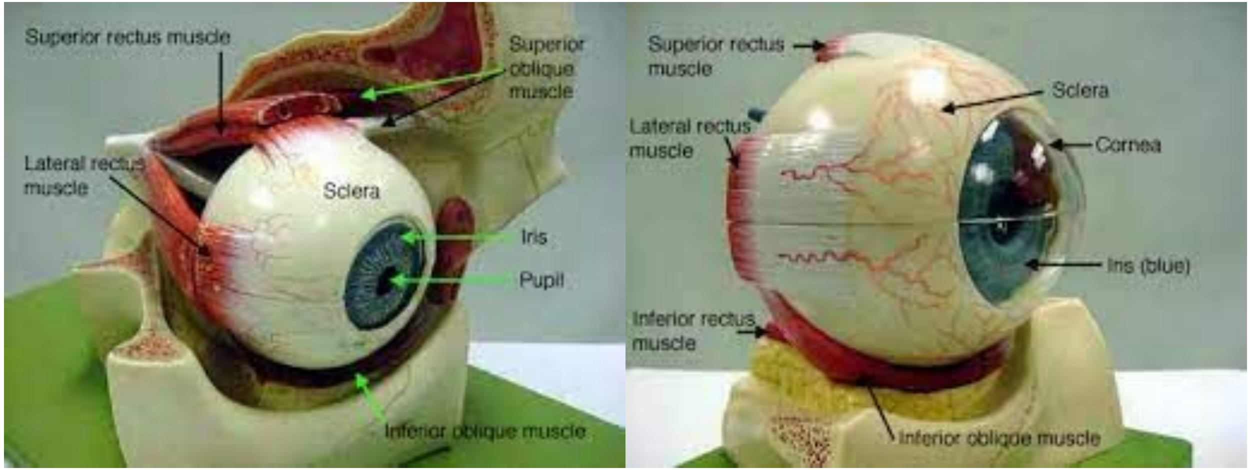

Fig 9. Anatomical model of the eyes

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Methods and Design - Eye Structure

Structure of the cornea

- Corneas often show astigmatism, and usually there is a greater radius of curvature at the horizontal than at the vertical meridian(**toricity**)
- Toric and conic models can be combined using more realistic **biconic surfaces**
- for each meridian and rotation angle ϕ:
  - Rx, Ry are principal radii of curvature
  - Qx, Qy are asphericity values

Biconic surface equation:

$$z(x,y) = \frac{\frac{x^2}{R_x} + \frac{y^2}{R_y}}{1 + \sqrt{1 - \frac{(1+Q_x)x^2}{{R_x}^2} - \frac{(1+Q_y)y^2}{{R_y}^2}}}$$

corneal diameter: 11.79mm
anterior cornea measurements [8]
Rx: 7.63±0.29mm
Ry: 7.4±0.28mm
Qx: -0.46±0.14mm
Qy: -0.48±0.14mm

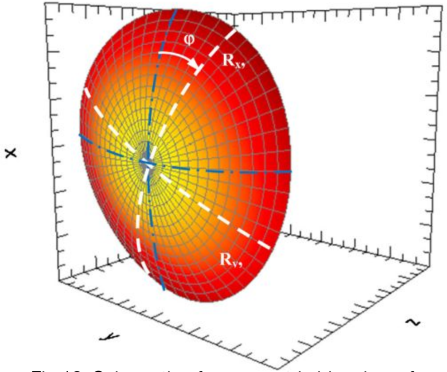

Fig 10. Schematic of a parametric biconic surface model

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Methods and Design - Eye Structure

Prevention of Blinking Alters Iris Configuration in Pigment Dispersion Syndrome and in Normal Eyes

- "Initial iris configuration was concave in all eyes with pigment dispersion syndrome, whereas in control eyes it was concave in four eyes, planar in four eyes, and convex in two eyes." [4]

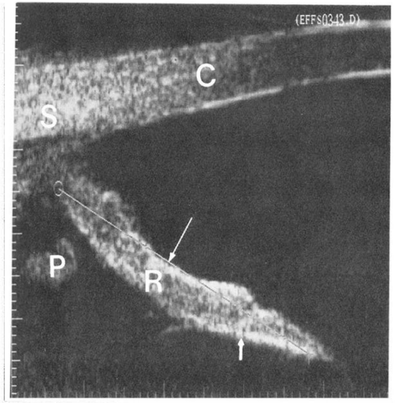

Fig 11.anterior segment ultrasound biomicroscopy of a concave iris (R) posterior to the reference line (large arrow). The cornea (C), sclera (S), and ciliary process (P) are visible.

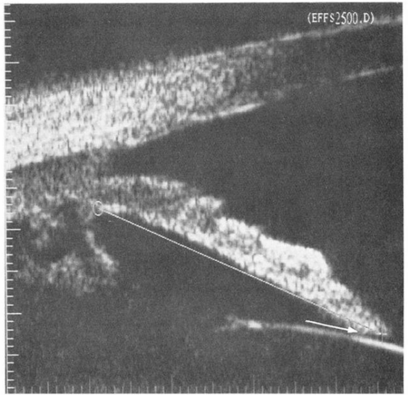

Fig 12. maximal change in iris configuration (now convex)

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Methods and Design - Modeling the Eye

The eye model was created in Blender 3.6 (computer graphics software):

- model the cornea as a biconic surface for anatomical accuracy
- Iris curvature depends on eye health, Iris can be flat or curved in our model
- utilize dense 3D head scan of 10 subjects for diversity
- use physiological parameters reported in previous research
- models head-slippage by generating random jittering

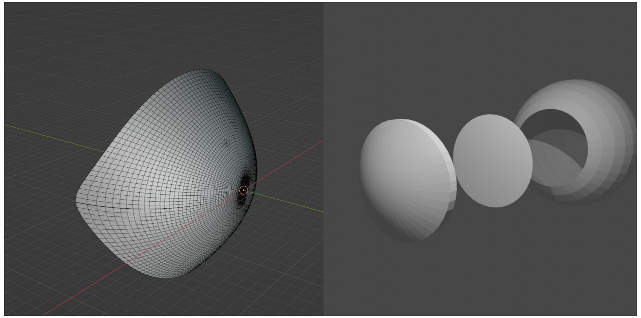

Fig 13. biconic surface generated in Blender 3.6 (on the left) and the 3 components of the mesh that makes up our eye model: cornea, iris, sclera (on the right)

Fig 14. Rendered view of our standalone eye model from on-axis view and perspective view in Blender 3.6

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Results & Discussion

- Modeled the refractive caustics of the cornea
- Created geometrically accurate sclera and cornea
- Automated scene setup and eye model creation using python scripting

Fig 15. Integration of our eye model with remeshed dense 3D head scan of subjects showing diverse human physiology (left and middle image). The image on the right shows previous model which is not anatomically accurate (Only the left eye was replaced with eye models)

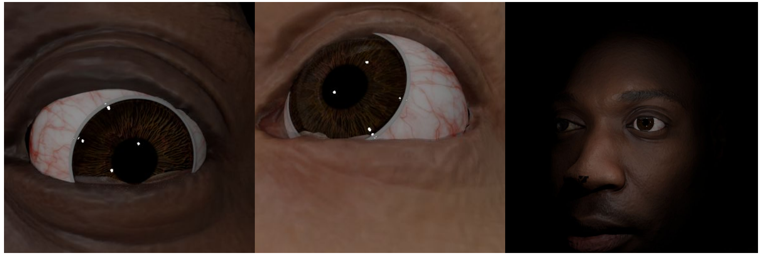

Fig 16. Rendered images from our model (left and middle images) and realistic lighting conditions (right image)

Results & Discussion

Gaze Tracking

6 layer convolutional neural net + 1 fully connected layer to estimate horizontal and vertical gaze angles

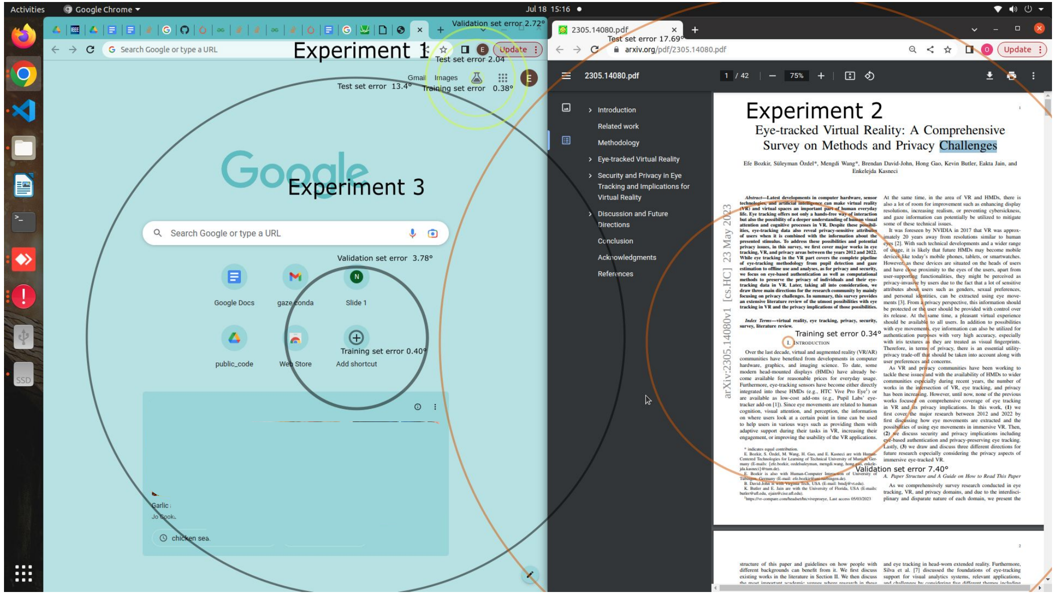

Fig 17. Visualizing gaze estimation error with real data only. 13 subjects were used in experiment 1 and the same subject was used for experiments 2 and 3 (data was not shuffled for experiment 2)

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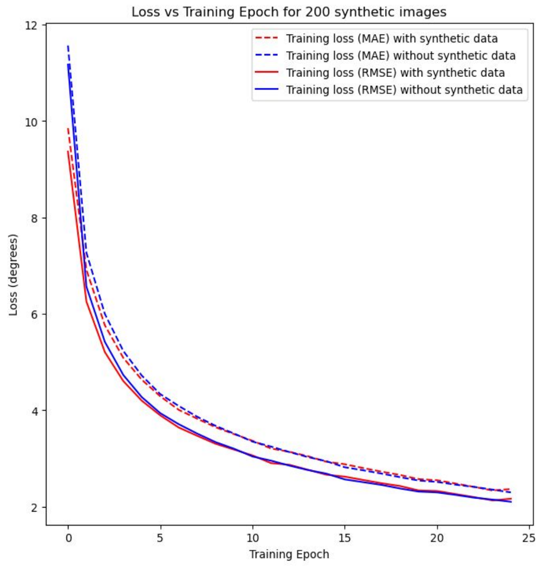
Results & Discussion

Trained a 6 layer convolutional neural network on 200 synthetic images. Performance initially improved by more than 2 degrees, but this improvement diminished due to the following limitations:

- Lack of additional synthetic data (ideally more than 100k)
- Current camera configurations is not accurate
- Textures need to be modeled with Infrared textures
- Skin texture can be improved to look more realistic



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Conclusion

Why is this important?

To ensure consistent and reliable results for a diverse range of individuals, it's vital to create equitable eye tracking technology which is underscored by its clinical applications including the diagnosis of conditions like Parkinson's and assistive technologies such as gaze-based text entry for people with limited motor function (i.e. cerebral palsy). One of the main goals of my research is to reduce bias related to diverse eye structures and human physiology.

Next Steps

- Will start fully automating the rendering process to render more images and increase the accuracy of the neural network
- Will start using infrared textures instead of textures in the visible spectrum
- Will determine the exact location of eye tracking cameras to improve the quality of synthetic images

Citations

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