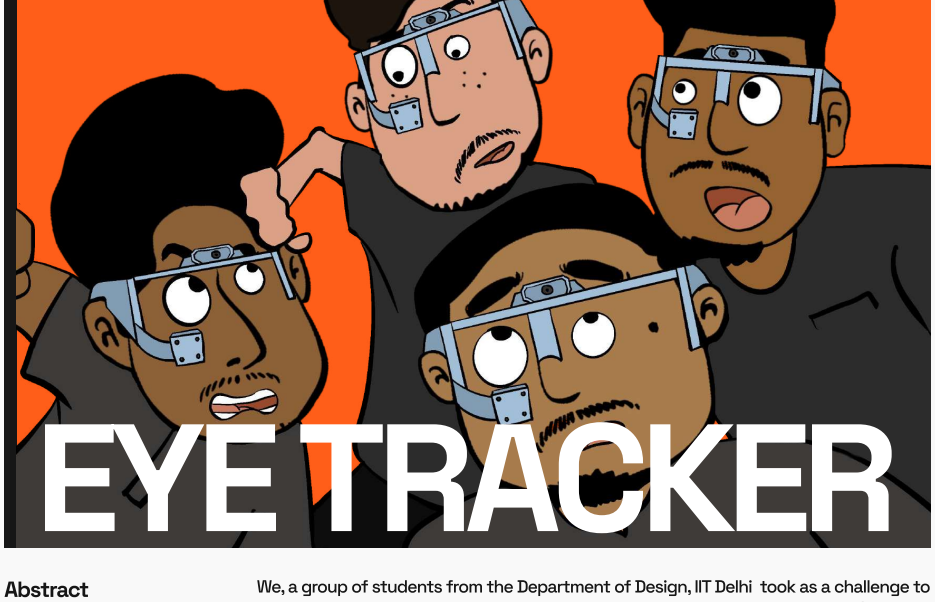


EYE TRACKER

Abstract

We, a group of students from the Department of Design, IIT Delhi took as a challenge to design a low cost eye-tracker that is accurate and intuitive as part of our Cognitive Ergonomics course in the fourth semester. This blog documents our learning experience, taking you from the core principles of eye-tracking right through to the design and build process.

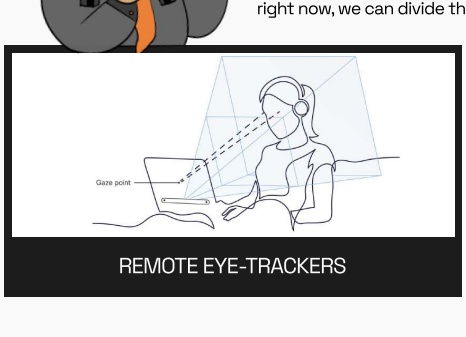
Hi there! We are team OMIT. We will be taking you through our eye-tracker project in detail. But before that we would like you to meet someone.
Hi! I am Prasad. I work as a security guard in IIT Delhi.

So Prasad being a security guard, a typical day in his life would be checking ID cards of students entering the Lecture Hall Complex at IIT Delhi. He wishes if there was faster way of checking ID cards. Let's give him the eye tracker that we built and see if it can make something better for him.

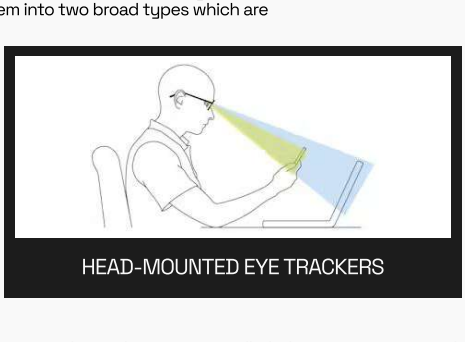
What is an eye tracker?

DEFINITION

In simple words, an eye tracker is a device that measures eye movements and determines where a person is looking. It essentially tracks the point of gaze or how your eyes move. This information has a wide range of applications in research, design, and even medical fields. If we take a look at all the eye trackers available in the market right now, we can divide them into two broad types which are



REMOTE EYE-TRACKERS



HEAD-MOUNTED EYE TRACKERS

REMOTE EYE TRACKERS

This type uses a camera positioned at a distance, typically below a screen, to track the user's eyes. They rely on infrared light to pinpoint the pupil and corneal reflection, calculating gaze direction. These systems can sometimes automatically adjust their view to compensate for head movements, offering a more hands-free experience.

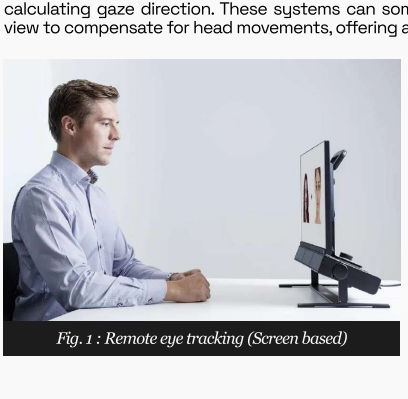


Fig. 1 : Remote eye tracking (Screen based)

Fig. 2 : Head stabilized eye tracking

HEAD-MOUNTED EYE TRACKERS

As the name suggests, these trackers are worn on the head, like glasses. They contain tiny cameras pointed at the eyes and often use infrared illumination for better pupil detection. This type allows for more freedom of movement compared to remote systems but can be bulkier and more expensive.

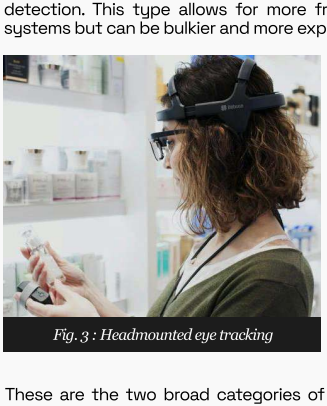


Fig. 3 : Headmounted eye tracking

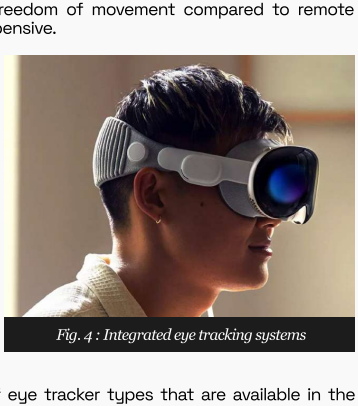
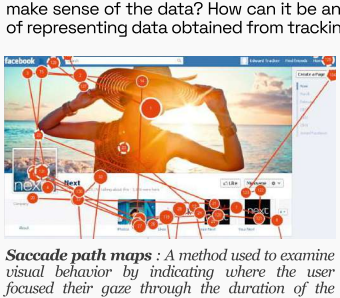


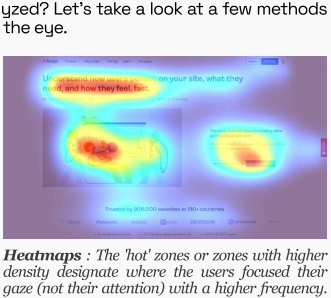
Fig. 4 : Integrated eye tracking systems

DATA REPRESENTATION

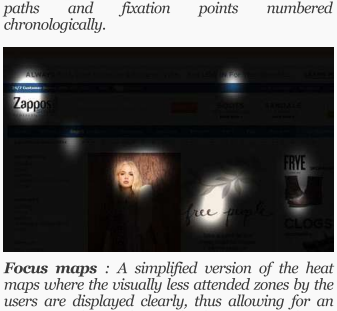
These are the two broad categories of eye tracker types that are available in the market. Now that we have the eye tracking data from using these devices, how do we make sense of the data? How can it be analyzed? Let's take a look at a few methods of representing data obtained from tracking the eye.



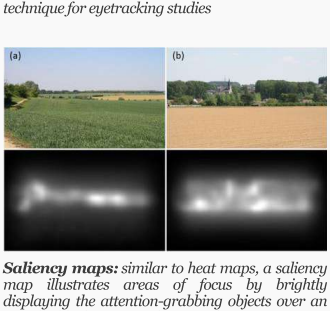
Saccade path maps : A method used to examine visual behavior by indicating where the user focused their gaze through the duration of the study. Represented by a combination of saccade paths and fixation points numbered chronologically.



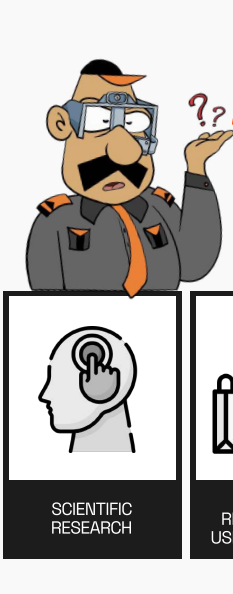
Heatmaps : The 'hot' zones or zones with higher density designate where the users focused their gaze (not their attention) with a higher frequency. Heat maps are the best known visualization technique for eyetracking studies



Focus maps : A simplified version of the heat maps where the visually less attended zones by the users are displayed clearly, thus allowing for an easier understanding of the most relevant information i.e., it provides more information about which zones were not seen by the users.



Saliency maps: similar to heat maps, a saliency map illustrates areas of focus by brightly displaying the attention-grabbing objects over an initially black canvas. The more focus is given to a particular object, the brighter it will appear



I see, but where is it used?

Eye tracking technology's versatility is evident by its applications across diverse fields. From scientific research to the world of entertainment, eye trackers provide valuable insights into human behavior. Let's explore five key areas where eye tracking proves particularly useful.

- SCIENTIFIC RESEARCH
- CONSUMER RESEARCH AND USER EXPERIENCE
- TRAINING AND SKILLS ASSESSMENT
- GAMING
- ASSISTIVE TECHNOLOGIES

SCIENTIFIC RESEARCH

Through eye tracking, researchers gain unique and objective insights into how we process information, allocate attention, and even hint at underlying emotions. This data empowers fields like psychology and neuroscience to understand human behavior and cognition in a profound way.

Eye tracking data can provide the behavioral end products of the cognitive processes (e.g., decisions) and isolate the different layers of related processes that occur during an experiment. In other words, Eye tracking grants continuous access to cognitive processes

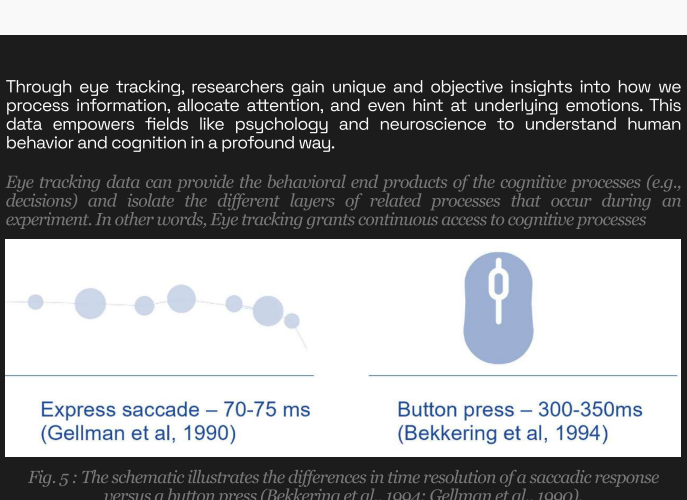


Fig. 5 : The schematic illustrates the differences in time resolution of a saccadic response versus a button press (Bekkering et al., 1994; Gellman et al., 1990).

CONSUMER RESEARCH AND USER EXPERIENCE

Eye tracking acts as a compass for consumer research and UX design. It pinpoints what grabs attention in marketing materials, optimizing product design and maximizing marketing impact. By revealing user navigation patterns, it empowers designers to craft intuitive interfaces and websites, leading to increased user satisfaction and engagement.

For example, you can look at 'How Heathrow airport uses eye tracking to improve wayfinding in Terminal 5' . The project aimed to understand how passengers navigate Terminal 5 to enable them to make wayfinding easier and more efficient in the future.

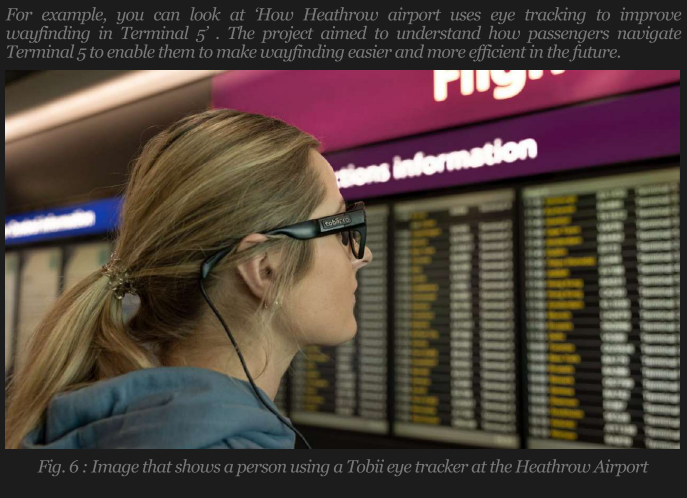


Fig. 6 : Image that shows a person using a Tobii eye tracker at the Heathrow Airport

TRAINING AND SKILLS ASSESSMENT

Eye tracking transcends mere knowledge transfer. It facilitates objective skill assessment by comparing new recruits' eye movements to experts, pinpointing areas for targeted training. This data informs the creation of optimal operating procedures, leading to faster skill acquisition, improved safety, and streamlined workflows.

The German Heart Center in Berlin has used eye tracking to examine the cognitive processes of perfusionists, to see how they respond to different stimuli and complications during a procedure, and how they distribute their attention across relevant equipment. This knowledge has been used to better articulate the process of operating the heart-lung machine and monitoring the patient's vital signs.

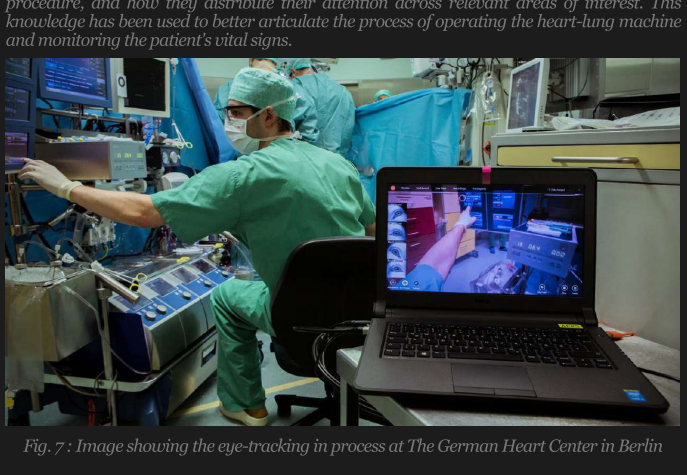


Fig. 7 : Image showing the eye-tracking in process at The German Heart Center in Berlin

GAMING

Eye tracking transforms gaming by enabling intuitive control through gaze. Players can aim, select, and interact in-game using their eye movements, creating a more immersive and natural experience. This technology opens doors for innovative game design and deeper player engagement.

With gaze-based target selection, you can lock onto targets by looking at them, enhancing your combat effectiveness. Tagging and tracking enemies is made easy as you can automatically mark them just by looking at them. Also, your initial aim is now determined by your eye's focus, offering more precision than moving your mouse to the target.

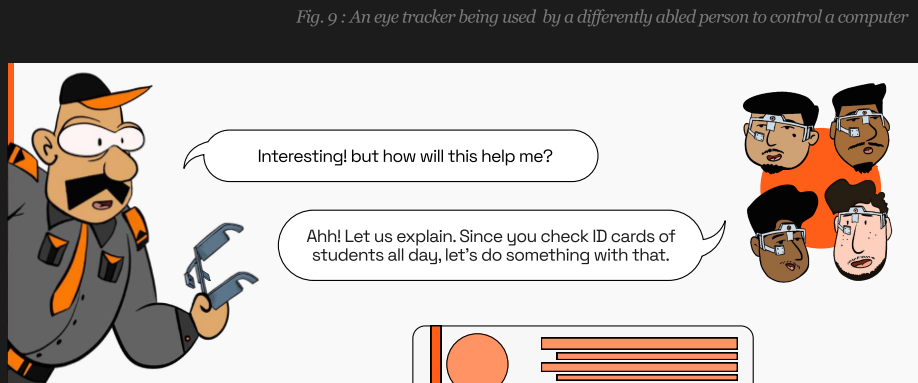
AIM AT GAZE
GHOST RECON
BREAKPOINT

Fig. 8: Snapshot of gaze-based target selection in action using Tobii eye tracker 5

ASSISTIVE TECHNOLOGIES

Eye trackers are increasingly utilized in assistive and rehabilitative applications, including controlling wheelchairs, robotic arms, and prostheses. By tracking eye movements and translating them into commands, these devices empower individuals with disabilities to enhance their independence and quality of life.

Fig. 9 : An eye tracker being used by a differently abled person to control a computer


Interesting! but how will this help me?
Ahh! Let us explain. Since you check ID cards of students all day, let's do something with that.

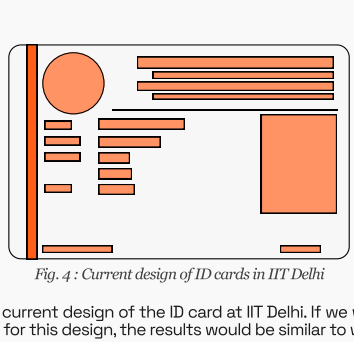


Fig. 4 : Current design of ID cards in IIT Delhi

You see, this is the current design of the ID card at IIT Delhi. If we were to conduct an eye tracking study for this design, the results would be similar to what's given below

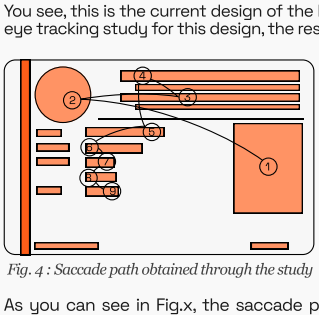


Fig. 4 : Saccade path obtained through the study

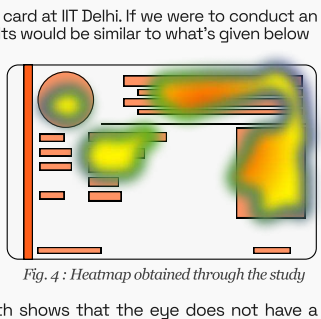


Fig. 4 : Heatmap obtained through the study

As you can see in Fig.x, the saccade path shows that the eye does not have a smooth and organic flow while looking at an ID card and the eye is also being distracted to data points that are not important. Now let's look at a new design of the ID card and conduct the same eye study with the new design to see how the results change.

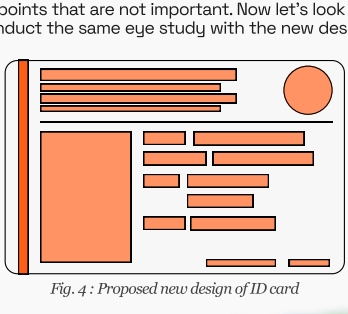


Fig. 4 : Proposed new design of ID card

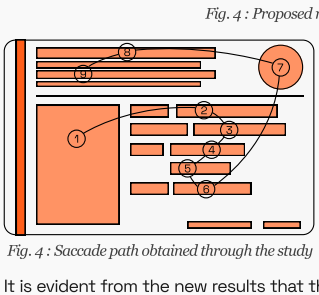


Fig. 4 : Saccade path obtained through the study

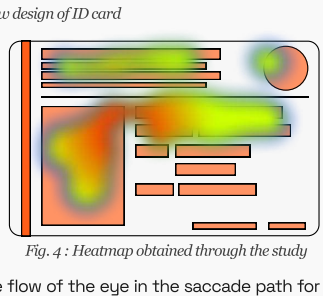
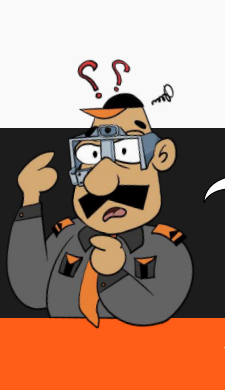


Fig. 4 : Heatmap obtained through the study

It is evident from the new results that the flow of the eye in the saccade path for the new design is much smoother and organic. Such a simple change could reduce the amount of time taken to look at a card and verify the person. Even if the difference is of a few seconds, since the activity is done repeatedly throughout the day it can have a significant effect on the efficiency of how security works within campus.



Oh cool! But how was this made?

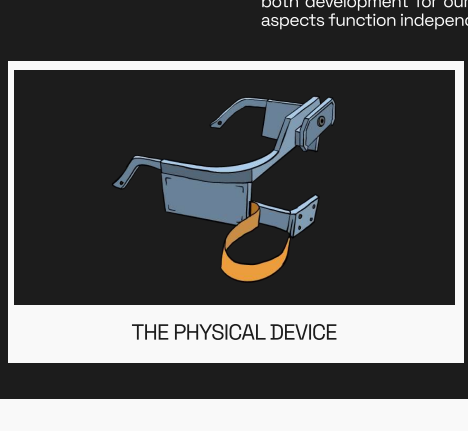
Before we dive into how we made the eye tracker, lets us explain what our initial vision was for this project.

Vision/Purpose:

To design a lightweight, easy to use, cheap, modular eye tracker for people of all ages irrespective of gender, ethnicity, profession etc.

This will help us to research further on the situational awareness aspects of the users when they are involved in daily activities, one such example could be the one demonstrated above;
What is the flow of movement of eyes when a security guard checks the ID card.

Based on our vision for the final product and its intended purpose, we concluded that a **head-mounted eye tracker** was the optimal solution. We then focused on designing a user experience that prioritized simplicity and efficiency. After exploring various options, we decided to divide the process into two distinct phases: first, users interact with the physical hardware to capture the scene and eye videos. Second, they utilize our software for tracking and data processing. This separation facilitated both development for our team and user interaction, as the hardware and software aspects function independently while making the product significantly cheaper.

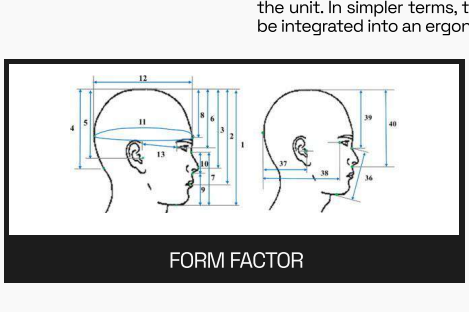


THE PHYSICAL DEVICE

SOFTWARE

THE PHYSICAL DEVICE

To delve deeper into the physical product's design, we can break it down further into two key aspects: human factors and ergonomics, and the components housed within the unit. In simpler terms, this clarifies what components will be used and how they'll be integrated into an ergonomic design.

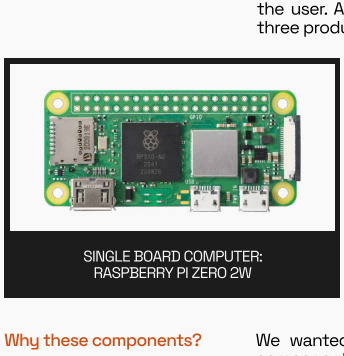


FORM FACTOR

COMPONENTS

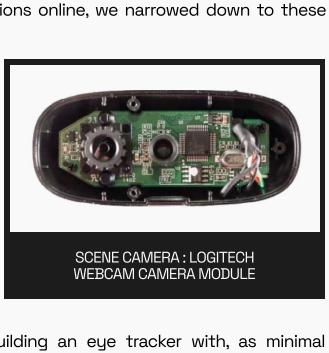
THE COMPONENTS

Since the physical device's only function is to record two videos at the same time, one of the eye and one of the scene, we started looking at single board computers and camera devices that could serve the purpose while being cheap. We wanted to keep a small form factor for the eye camera since it should not obstruct the view of the user. After looking through various options online, we narrowed down to these three products for our device:



SINGLE BOARD COMPUTER: RASPBERRY PI ZERO 2W

EYE CAMERA : RASPBERRY PI CAMERA MODULE



SCENE CAMERA : LOGITECH WEBCAM CAMERA MODULE

Why these components?

We wanted to make sure that we are building an eye tracker with, as minimal components required, to align it with our vision, of making the eye tracker as cheap as possible, easy to build, easy to assemble, such that maintenance is easy, as well as easy to find the components.

Now, let's look at how we can integrate these components to create a comfortable, ergonomic head-mounted device that accommodates nearly everyone.

We aim for the headgear to be ergonomically designed so that it fits individuals across a wide spectrum, from 5th percentile women to 95th percentile men, including children above the age of 12 and individuals wearing cultural or religious attire.

THE FORM FACTOR

Once we finalized on what components to use all that is left is to design an ergonomic form factor. Our goal was to make this a one-size-fits-all version, so we took in consideration human anthropometric data of 5%ile female to 95%ile male. For this we went ahead with a seven stage process where we went from defining adjectives for the form factor to finally 3D printing the model which is explained below:

- Research: ADJECTIVES, MOOD BOARDS, FORM BOARDS
- Ideation: CONCEPTS, MOCKUPS
- Prototyping: CAD, 3D PRINT

1 ADJECTIVES

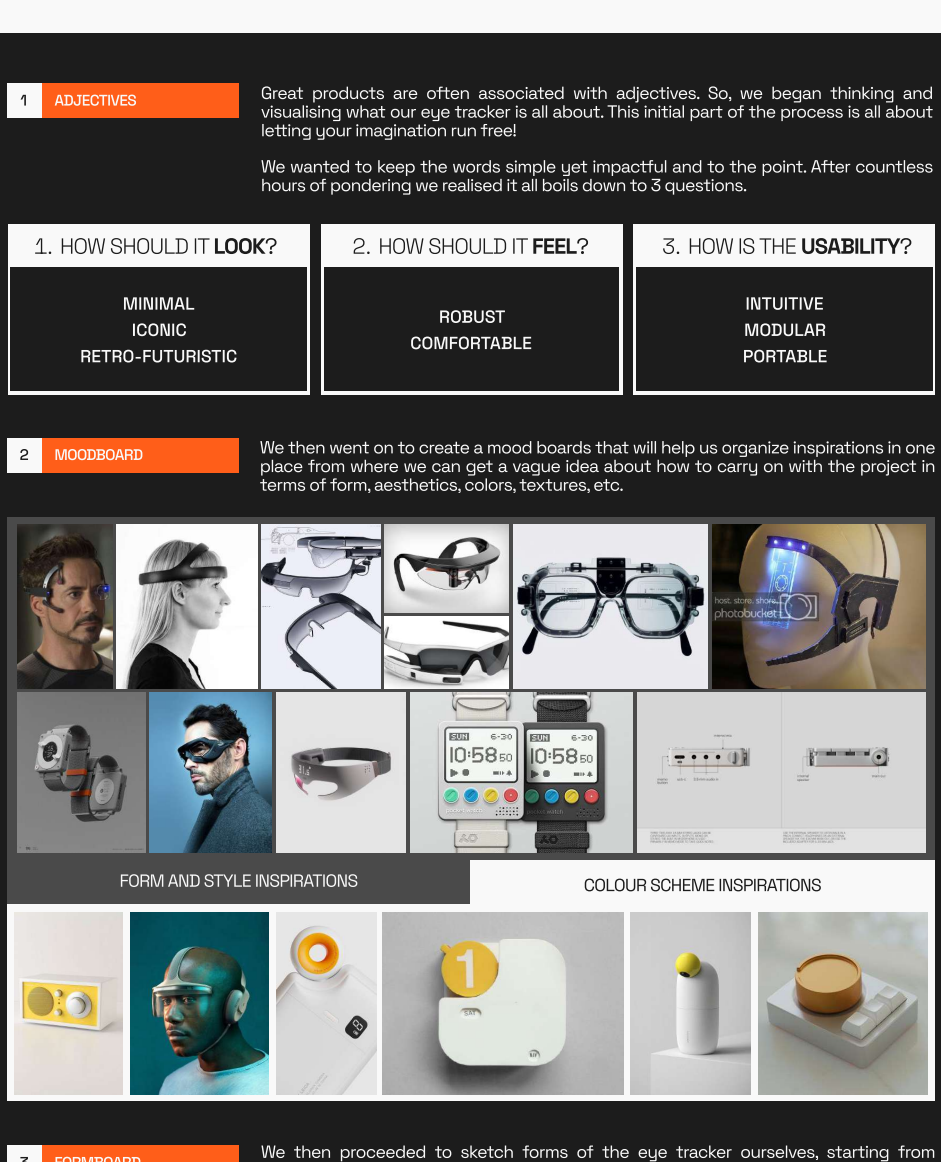
Great products are often associated with adjectives. So, we began thinking and visualising what our eye tracker is all about. This initial part of the process is all about letting your imagination run free!

We wanted to keep the words simple yet impactful and to the point. After countless hours of pondering we realised it all boils down to 3 questions.

1. HOW SHOULD IT **LOOK?**	2. HOW SHOULD IT **FEEL?**	3. HOW IS THE **USABILITY?**
MINIMAL ICONIC RETRO-FUTURISTIC	ROBUST COMFORTABLE	INTUITIVE MODULAR PORTABLE

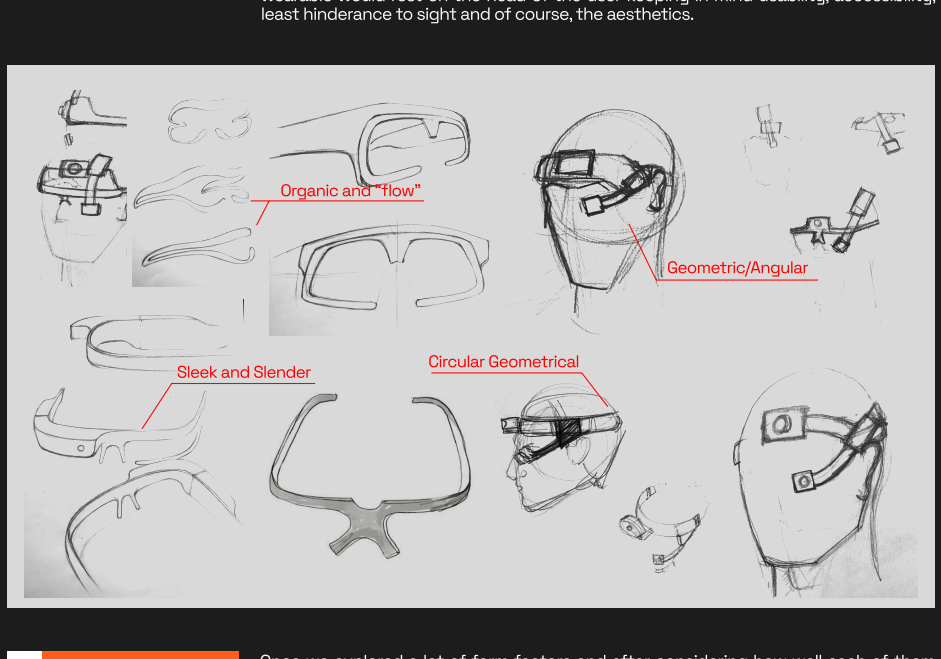
2 MOODBOARD

We then went on to create a mood boards that will help us organize inspirations in one place from where we can get a vague idea about how to carry on with the project in terms of form, aesthetics, colors, textures, etc.



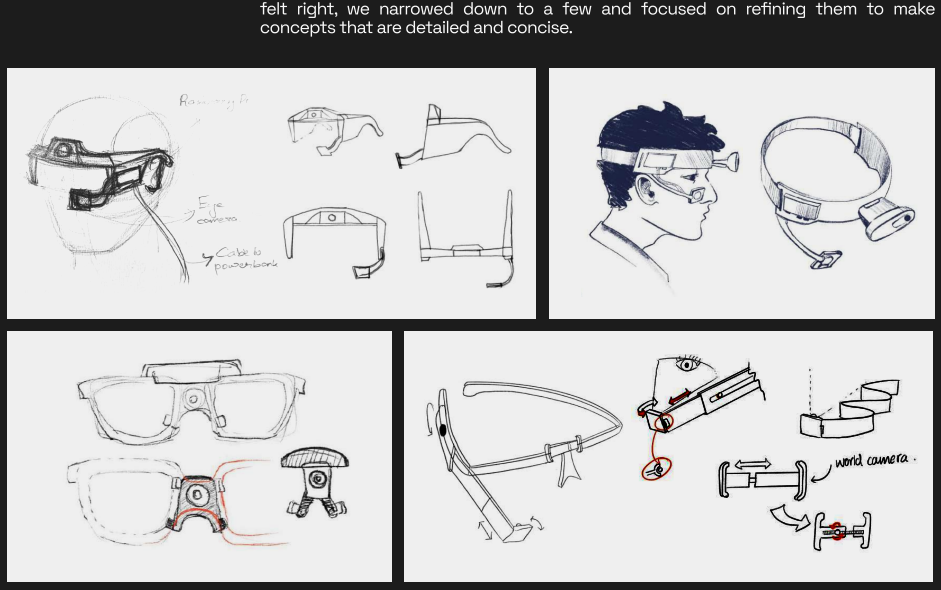
3 FORMBOARD

We then proceeded to sketch forms of the eye tracker ourselves, starting from abstract forms and moving to more realistic ones. We explored different ways the wearable would rest on the head of the user keeping in mind usability, accessibility, least hinderance to sight and of course, the aesthetics.



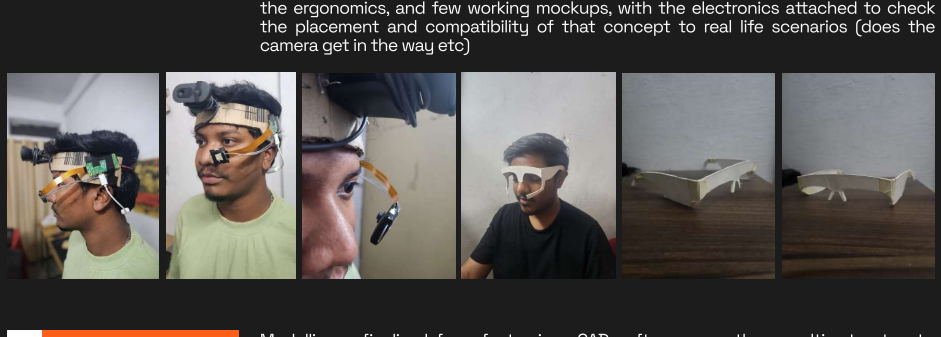
4 CONCEPTS

Once we explored a lot of form factors and after considering how well each of them matches with the adjectives, usability and accessibility of design, and simply what felt right, we narrowed down to a few and focused on refining them to make concepts that are detailed and concise.



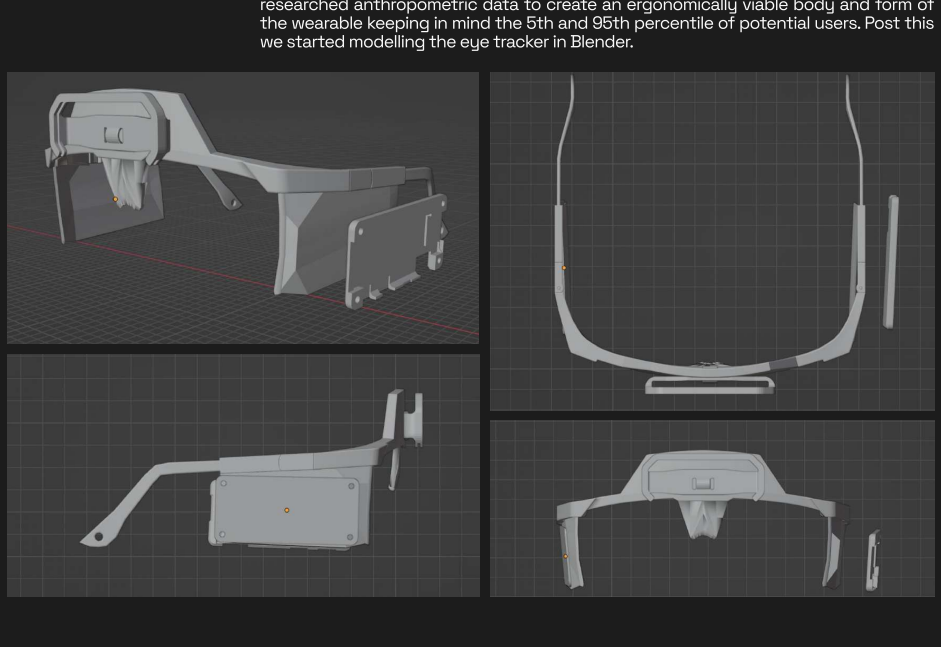
5 MOCKUPS

These sketches were brought to life in the form of mockups, where we tried replicated the forms and sketches made in earlier steps. The goal of these mockups was to check the usability of each concept. We made few low fidelity mockups, just to check the ergonomics, and few working mockups, with the electronics attached to check the placement and compatibility of that concept to real life scenarios (does the camera get in the way etc)



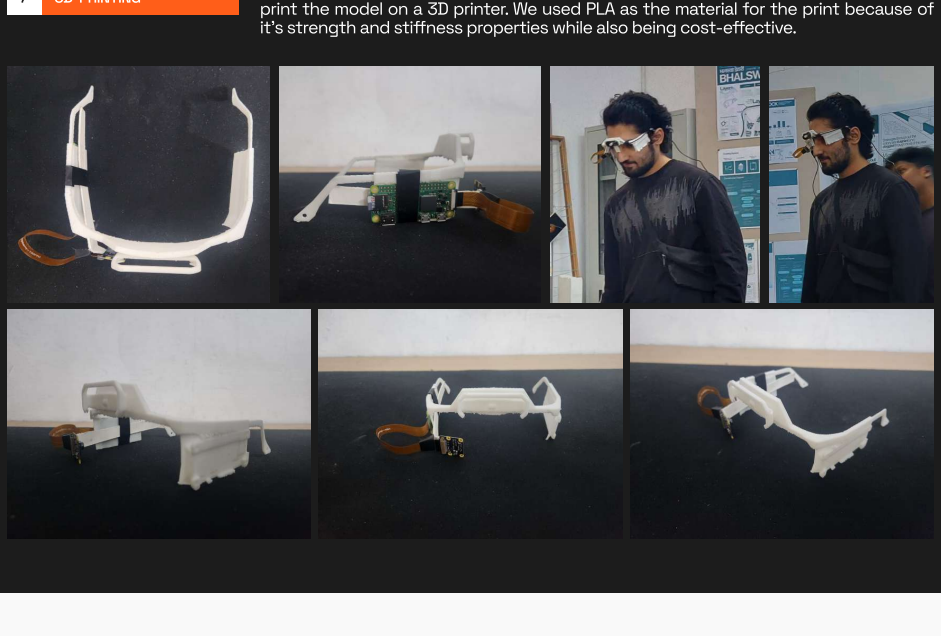
6 CAD MODELLING

Modelling a finalized form factor in a CAD software was the penultimate step to achieving a final prototype of the eye tracker. We measured the dimensions of all electronic components in order to design the housing for it accordingly. We also researched anthropometric data to create an ergonomically viable body and form of the wearable keeping in mind the 5th and 95th percentile of potential users. Post this we started modelling the eye tracker in Blender.



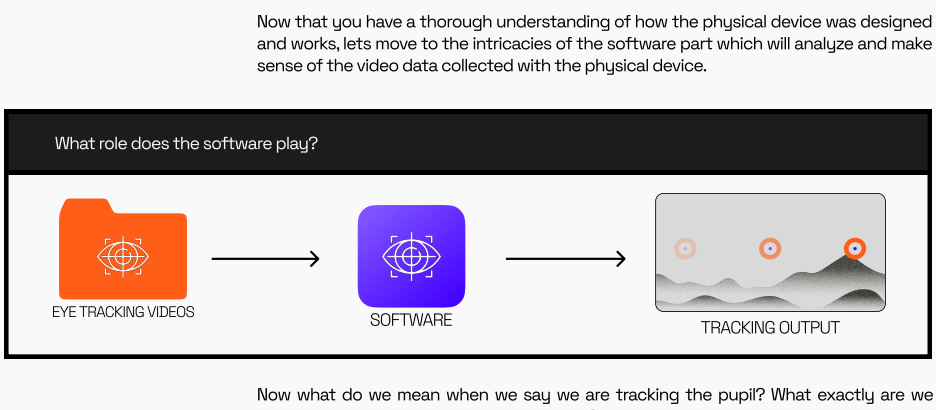
7 3D-PRINTING

Once we had a final 3D model with the dimensions and scale set, we proceeded to print the model on a 3D printer. We used PLA as the material for the print because of it's strength and stiffness properties while also being cost-effective.



THE SOFTWARE

Now that you have a thorough understanding of how the physical device was designed and works, lets move to the intricacies of the software part which will analyze and make sense of the video data collected with the physical device.



Now what do we mean when we say we are tracking the pupil? What exactly are we looking for when the tracking is being done?

The process of an eye seeing anything in realtime can be broken into 3 categories, and these are 3 categories that we are focusing at when we are tracking the eye.

- FIXATIONS
- SACCADES
- PSO's

FIXATIONS

These are periods where our **eyes remain relatively still, focusing on a specific point** of interest in our field of view. During fixations, we gather most of the visual information we need. The duration of a fixation can vary depending on factors like complexity of the scene and individual differences.

SACCADES

In contrast to fixations, saccades are the **rapid, jerky movements our eyes make to shift our gaze from one point of interest to another.** Saccades are very fast, happening in milliseconds, and allow us to explore a wide area of our visual field without having to move our head constantly.

PSO (Post Saccadic Oscillations)

These are tiny, involuntary tremors of the eye that can sometimes occur after a saccade. PSOs are much smaller and slower than saccades themselves, and their purpose isn't entirely understood. Some theories suggest they help fine-tune the eye's position after a saccade or might be a byproduct of the saccadic movement itself.

Now that we have understood what we are tracking, we did a pilot research on how we can track the fixations, saccades and PSO's of the pupil and realized there are many ways in which this is possible. We also found that the use of Artificial Intelligence/ Machine Learning technologies to be a good fit for the purpose.

While looking through different methods and techniques that make use of AI/ML for tracking the pupil, we found that we can make use of Classification or Regression methods to train an AI/ML model that can track the pupil and give the desired output.

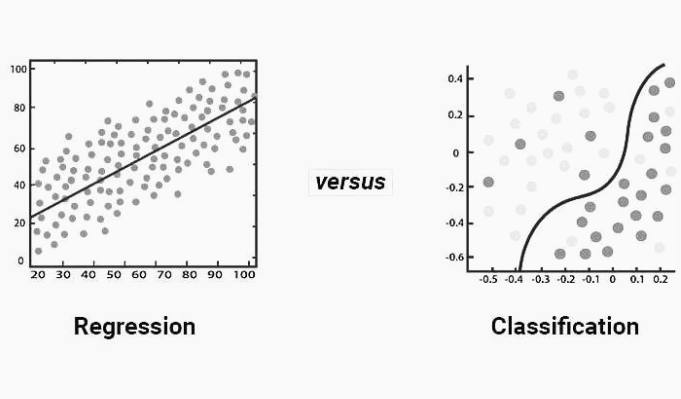
All ML **models take input variables known as "features"** then process it it with the particular model's respective algorithm and **produces an output which is a "prediction".** In our case the coordinates of where the eye is looking.

Features → **Model** → **Prediction**

eg. Position of Pupil, Iris Features, Eyelid position

eg. Log. Regression, CNN Classification, Support Vector Machine

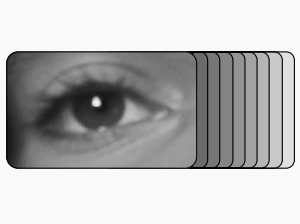
eg. Coordinates of the eye



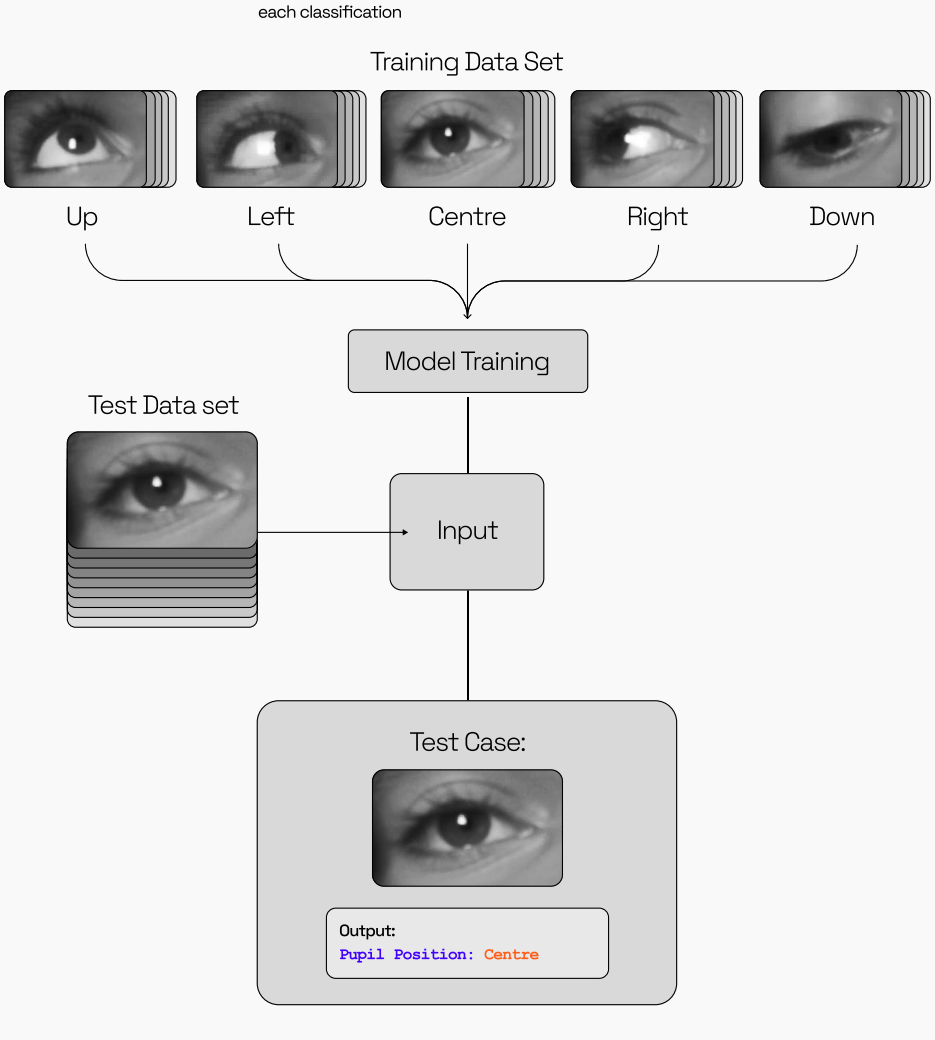
FOR OUR PROJECT

For our project we first started off trying the Linear Regression method

After capturing the video of eye, we extract the frames out of the calibration phase of the eye tracker video in order to train the Regression model



300 photos were classified into 5 groups for the training part, with roughly 60 photos in each classification

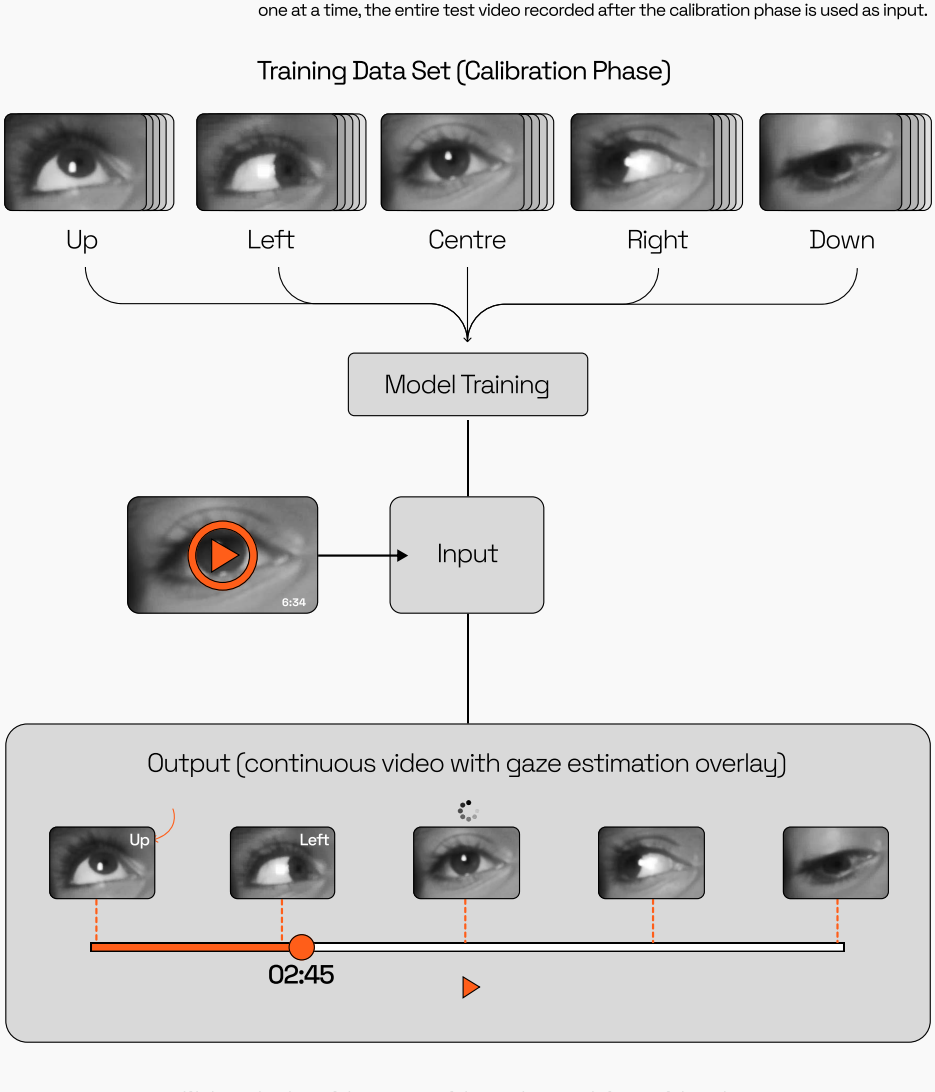


```
Output:
Pupil Position: Centre
```

TRYING OUT A NEW MODEL

Next we moved to the Classification based CNN model

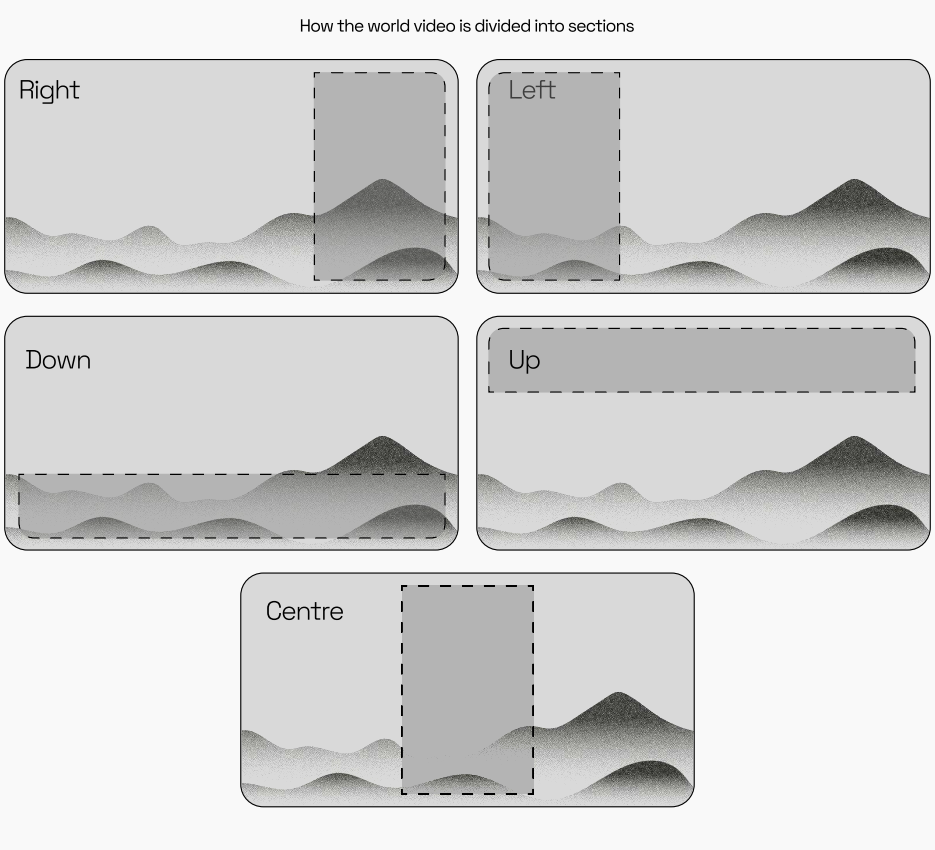
The initial model training part was similar to the one did in Regression model, the difference here was the input for the experiment. Instead of inputing number of photos one at a time, the entire test video recorded after the calibration phase is used as input.


Training Data Set (Calibration Phase)
Up
Left
Centre
Right
Down
Model Training
Input
Output (continuous video with gaze estimation overlay)
Up
Left
02:45

We have the data of the position of the pupil w.r.t each frame of the video.

Frame no.	Position
01.	Left
02.	Left
03.	Centre
04.	Centre
05.	Right
06.	Right

How the world video is divided into sections

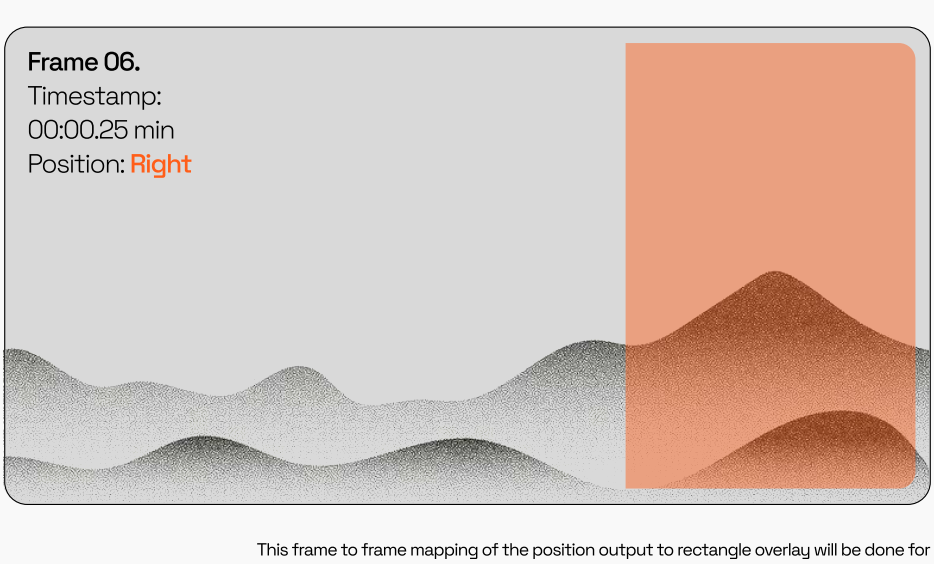


CONFUSING? LETS MAKE IT EASIER FOR YOU

Now the output we receive from both methods, will be used to overlay a rectangle over the video that was captured with the world view camera.

For example, lets take this case:
Frame 06. Corresponding to to timestamp 00:00.25 min of the video, with position of eye as right.

So the worldview video, with the rectangle overlay for the 6th frame of the worldview video will look something like:



This frame to frame mapping of the position output to rectangle overlay will be done for the entire video automatically, in order to get the gaze estimation for the user.

THE CHOSEN MODEL

The final method tried for tracking the pupils:

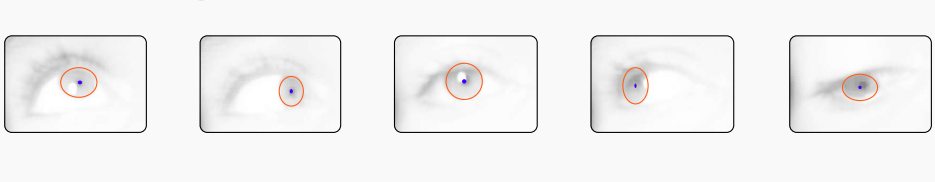
After we learned the basics of what the Machine Learning models can do and are capable of, we moved a level higher, to get better precision in predicting the accurate position of eyes, and therefore the gaze.

In this method, the user has to give the eye tracked video as the input.

1. The application first breaks the video into individual frames

2. Then, we convert every image into a very high contrast image, in order to differentiate the pupil, apart from the eyeball/environment

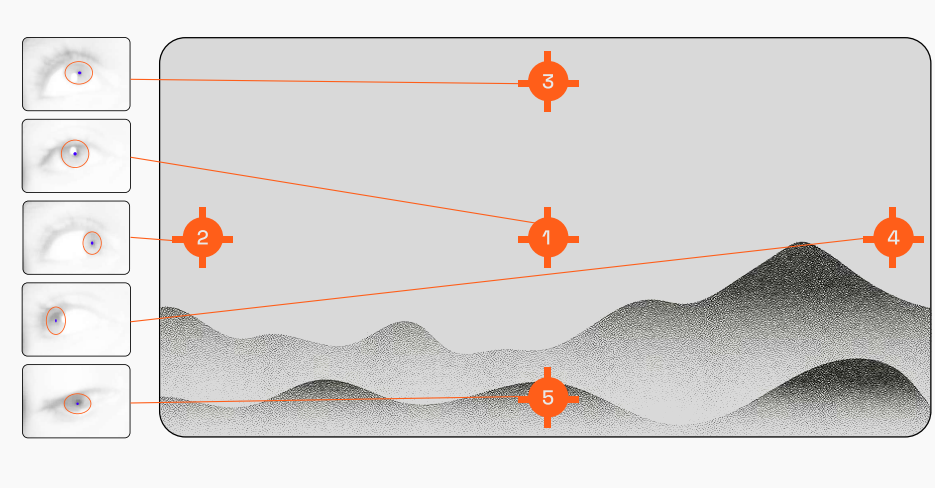
3. Further, with the help of OpenCV Libraries, we create an ellipse around the iris, and mark it's centre to locate the position of the pupil.



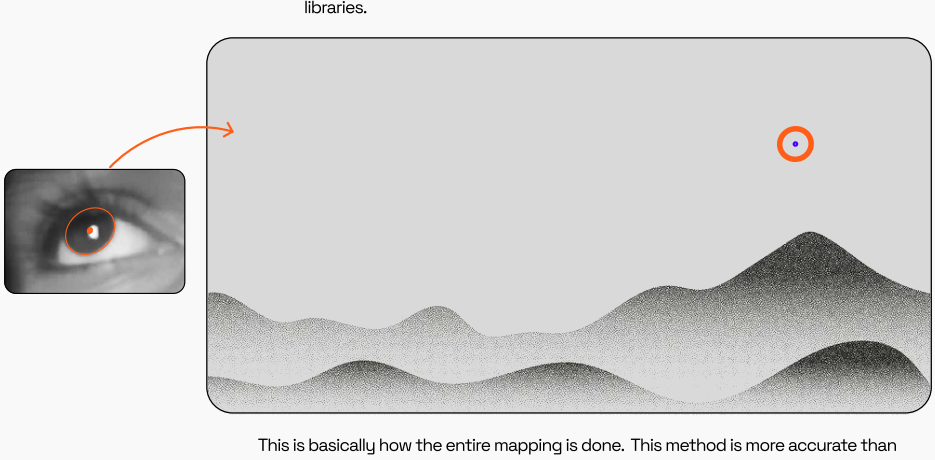
4. The shape of the ellipse, along with it's centre, will be used to map the coordinates for over the World view footage.

This is done in the following steps:

a. The calibration phase coordinates are mapped to the world view frames.



b. Once the Calibration Phase Eye positions are mapped, rest of the eye positions can be easily mapped. This is done by OpenCV mapping provided in the OpenCV libraries.



This is basically how the entire mapping is done. This method is more accurate than others, since we are projecting every coordinate on to the world view screen and getting the gaze estimation.

A USER'S GUIDE

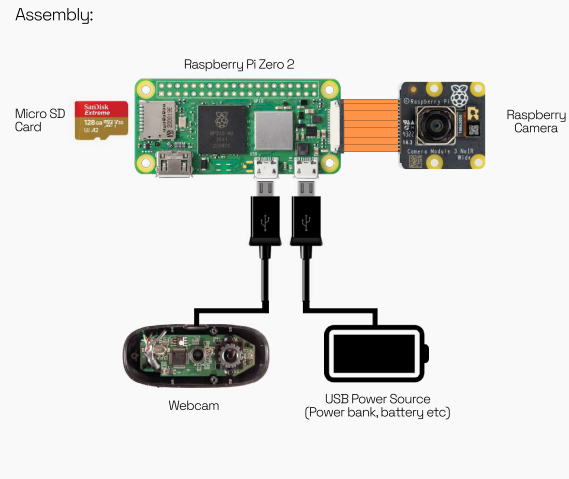
How to use the eye tracker that we have just made?

To understand that, we have divided the process of using it into three parts. Before starting the shoot, During the shoot, and After the shoot is completed. Each of these stages is explained in detail below.

- Before starting the shoot
- During the shoot
- After the shoot is completed

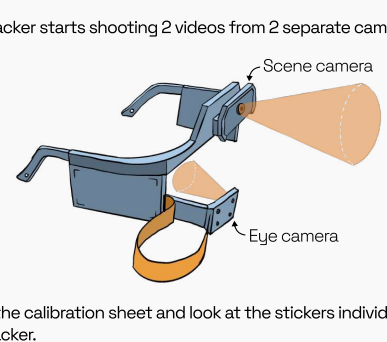
BEFORE

Assembly:

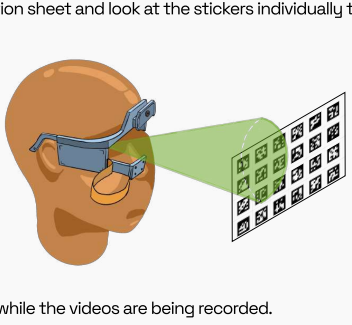


DURING

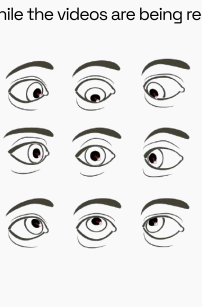
1. The eye tracker starts shooting 2 videos from 2 separate cameras



2. You place the calibration sheet and look at the stickers individually to calibrate the eye tracker.

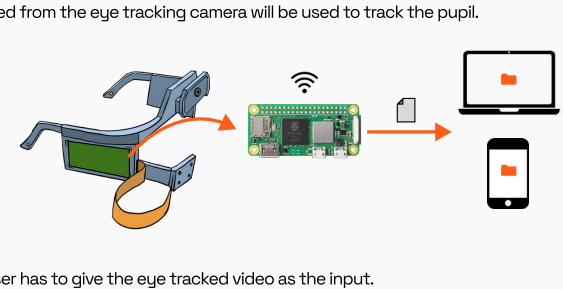


3. Start looking around while the videos are being recorded.

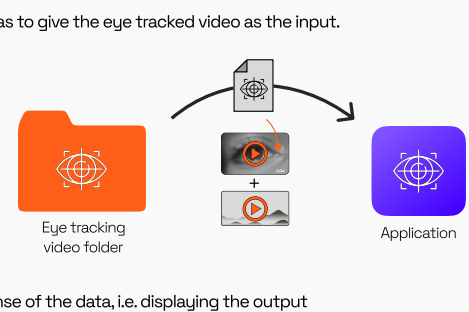


AFTER

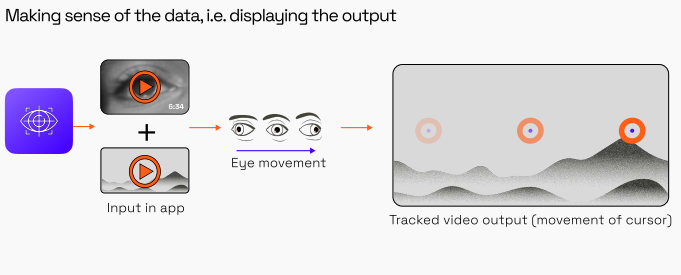
1. The two videos that are shot from the 2 cameras are sent to your phone/laptop device with the help of the Raspberry Pi Chip of the Eye-tracker. The video that we have received from the eye tracking camera will be used to track the pupil.



2. The user has to give the eye tracked video as the input.



3. Making sense of the data, i.e. displaying the output



FUTURE PROSPECTS

Eye trackers do more than follow your gaze. They can measure blink rate, heat maps, and pupil dilation for deeper insights. We're planning to incorporate these features in future versions, so **stay tuned.**

- HEAT MAPPING
- BLINK RATE
- PUPIL DILATION

SUMMARY

So, now that we know,

- What is an eye tracker is,
- Where it is used,
- How it is made, both the software and hardware part,
- How to use one, etc

So we guess you are ready to make one yourself, and try it out, right?

To make one yourself, you can use the **following resources** that helped us make one.

RESOURCES

Research Papers

Tomaž Čegovnik , Kristina Stojmenova, Grega Jakus, Jaka Sodnik (2018). An analysis of the suitability of a low-cost eye tracker for assessing the cognitive load of drivers

Keiron O'Shea, Ryan Nash (2015, Decemeber) An Introduction to Convolutional Neural Networks

Shaharam Eivazi, Thiago Santini, Thomas C. Kübler, Enkelejda Kasneci (2018, June) An Inconspicuous and Modular Head-Mounted Eye Tracker

Tianxing Li, Xia Zhou (2018) Battery-Free Eye Tracker on Glasses Battery-Free Eye Tracker on Glasses

Kyle Krafka, Aditya Khosla, Petr Kellnhofer, Harini Kannan, Suchendra Bhandarkar, Wojciech Matusik, Antonio Torralba (2016) Eye Tracking for Everyone

Radoslaw Mantiuk, Michal Kowalik, Adam Nowosielski, and Bartosz Bazyluk (2012, January) Do-It-Yourself Eye Tracker: Low-Cost Pupil-Based Eye Tracker for Computer Graphics Applications

Hélio Clemente Cuve, Jelka Stojanov, Xavier Roberts-Gaal, Caroline Catmur, Geoffrey Bird (2021, June) Validation of Gazepoint low-cost eye-tracking and psychophysiology bundle

Jason S. Babcock, Jeff B. Pelz, Joseph Peak (2003, February) The Wearable Eyetracker: A Tool for the Study of High-level Visual Tasks

Open-source Repositories

- https://github.com/Yutaltoh/3D-Eye-Tracker
- https://github.com/pupil-labs/pupil?tab=readme-ov-file
- https://github.com/esdalmaijer/webcam-eyetracker
- https://github.com/simonarvin/eyeloop?tab=readme-ov-file#getting-started

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