Measuring Visual Acuity in Bees from High-Resolution Images

Xin Wang[1], Kaylin Roberts[1], Eitan Rashkovan[1], Evan Ji, Todd Oakley[1], Eleanor Caves[1,2], Gia Ahn[1]

[1] University of California, Santa Barbara; [2] Caves Lab

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Abstract

Visual acuity, the ability to perceive detail, is ecologically important, as it dictates what aspects of a visual scene an animal can resolve. The study of visual acuity in bee species helps biologists understand their evolutionary history and gain insight into their foraging strategies and navigation abilities. Sponsored by the Caves Lab, this project aims to design a pipeline that uses **high-resolution 2D photos** taken by the NSF-funded *Big Bee Project* to estimate visual acuity across different bee species. In the pipeline, we develop algorithmic approaches to measure the diameter of the **ommatidia** and estimate the **interommatidial angles** on the eye's surface. By achieving a significant level of automation and accuracy, our pipeline will facilitate more efficient data collection for biologists.

Introduction

Previous studies have relied on painstaking manual counts and estimates to describe compound eye structure. So, we focus on utilizing 2D bee photos to expedite the data collection process. The following are key quantities in our work

- *ommatidia*: individual hexagon-like units that make up the compound eyes of insects and its diameter D refers to the width of hexagon and represents the **sensitivity to light**
- *Interommatidial angle* ϕ: angular separation between adjacent ommatidia in the compound eyes, representing the field of view that each ommatidium covers
- *Cycle per Degree(CPD)*: the number of distinct line pairs, or cycles, that can be perceived within one degree of the visual field. A higher CPD value indicates finer visual acuity and the ability to **discern smaller details** or patterns.

$$CPD = 1 / (2 \times \phi * 180° / \pi)$$

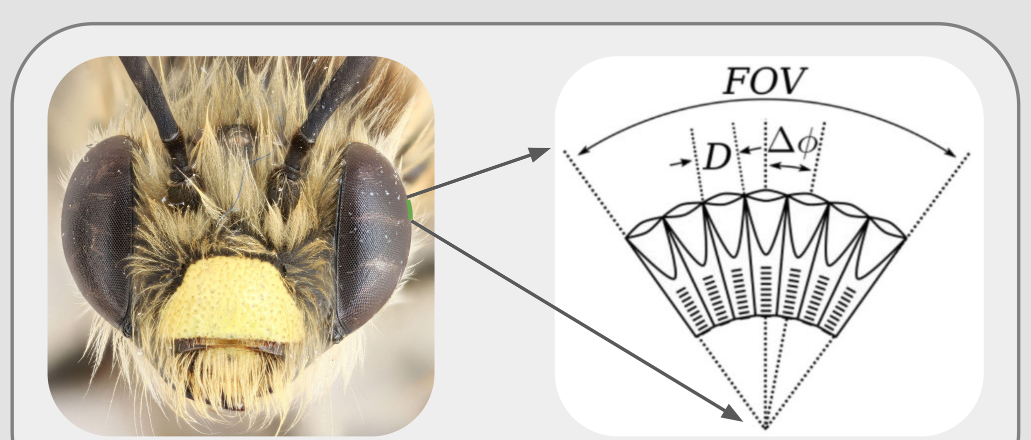

Figure 1. Visualization of the Compound Eye Structure

Datasets

The Bee Library is an online repository housing bee image, trait, and specimen data. We bulk downloaded **Head Frontal** and **Habitus Lateral** images for each bee and organizing them into a folder named by the bee's **catalog number**. Currently, our data focused exclusively on 145 bee specimens collected at UCSB Cheadle Center. Each image was obtained by synthesizing multiple identical 6000*4000 pixel bee photos with varying focal points, allowing for the creation of high-resolution representations of different sections of the bee. A scale bar for length measurements is available in each image.

For the contour analysis, we perform eye segmentation on the head frontal images, extracting both **eye bitmaps** and converting them into binary images. Each bee's traits, such as **Family** and **Sex**, are stored separately in a csv file.

Figure 2. Images and Biological Traits of a Bee Specimen

Methodology

The following figure describes how we collect a bee's visual acuity parameters through a rigorous pipeline. In short, we

1. measure the ommatidia diameter with a 2D ODA
2. use a pretrained segmentation model(**SAM**) to segment the shape of eye
3. approximate the shape of the eye by a continuous curve
4. simulate ommatidia(points) on the curve with the ommatidia diameter and derive interommatidial angles

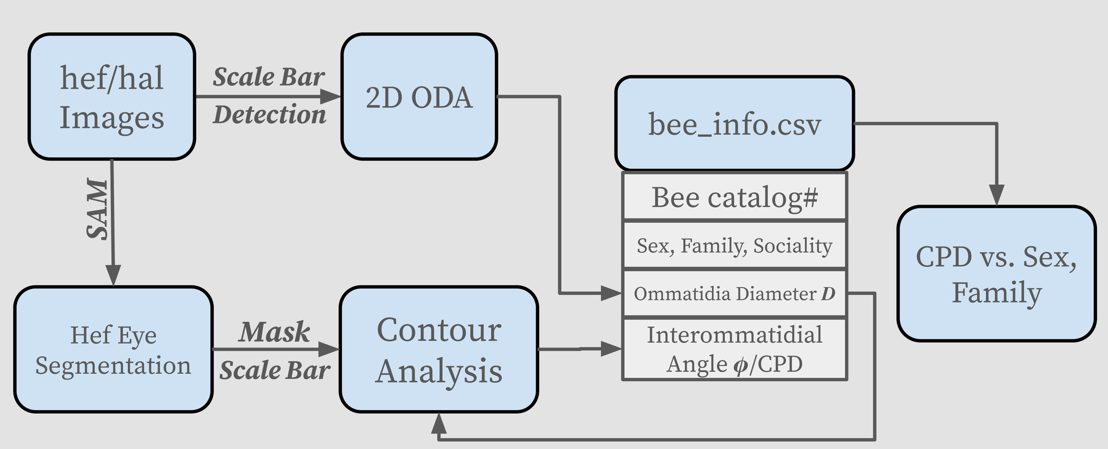

Figure 3. The pipeline for Visual Acuity Measurements

Here, we briefly introduce algorithms of some important steps.

The Eye Segmentation (SAM)

Input: a head frontal image X

Define: simple mouse clickings

1. a bounding box $B = ((x_1,y_1),(x_2,y_2))$ that crops a bee's eye
2. a list of points $P = ((x_1,y_1),(x_2,y_2),\ldots)$
3. a list $s = [1,0,\ldots]$ that indicates positive and negative points

Output: a binary mask M

$$M = SAM(X,B,P)$$

Ommatidia Detection Algorithm (2D ODA)

Input: a habitus lateral image X and a polygon m inside M

Algorithm: inside the polygon m

1. generate a 2D fast fourier transform
2. find the three fundamental gratings as the local maxima
3. use autocorrelation to amplify the periodic elements
4. filter higher image frequencies
5. invert the filtered 2D fast fourier transform
6. finds local maxima(ommatidia) in the inverted image

Output: # ommatidia N, mean ommatidia diameter D, S^2

Contour Analysis

Input: a left or right eye mask M, mean ommatidia diameter D

Algorithm:

1. extract and segment the eye contour $C = [(x_1,y_1),(x_2,y_2),\ldots]$
2. rotate the contour segment and get C' for curve fitting
3. define # sample points **n**
4. **for** $i = 1,2,\ldots,N_1$ **do**
   a. sample a list of points $S_i = ((x_1,y_1),\ldots,(x_\square,y_\square))$ on C'
   b. fit S_i to a quadratic regression $f_i(x)$, where $x \in [x_1,x_\square]$
   c. **if** f_i's $SSe \leq \alpha$ **do**
      i. **for** $j = 1,2,\ldots,N_2$ **do**
      ii. sample one ommatidia $o_1 = (x_1,f_i(x_1))$ on f_i
      iii. find o_2, where the arc length $L(o_1,o_2) \approx D$ on f_i
      iv. find o_1,o_2's normal lines l_1,l_2 on f_i
      v. calculate the angle $\phi_{i\square}$ between l_1 and l_2

Output: a list of angles $[\phi_{11},\phi_{12},\ldots]$

Results

We first present the results from a single bee UCSB-IZC00003796, where the estimation of ommatidia diameter D and interommatidial angle ϕ are visualized as histograms below. By adopting mean in both cases, we have $CPD \approx$ **0.442**.

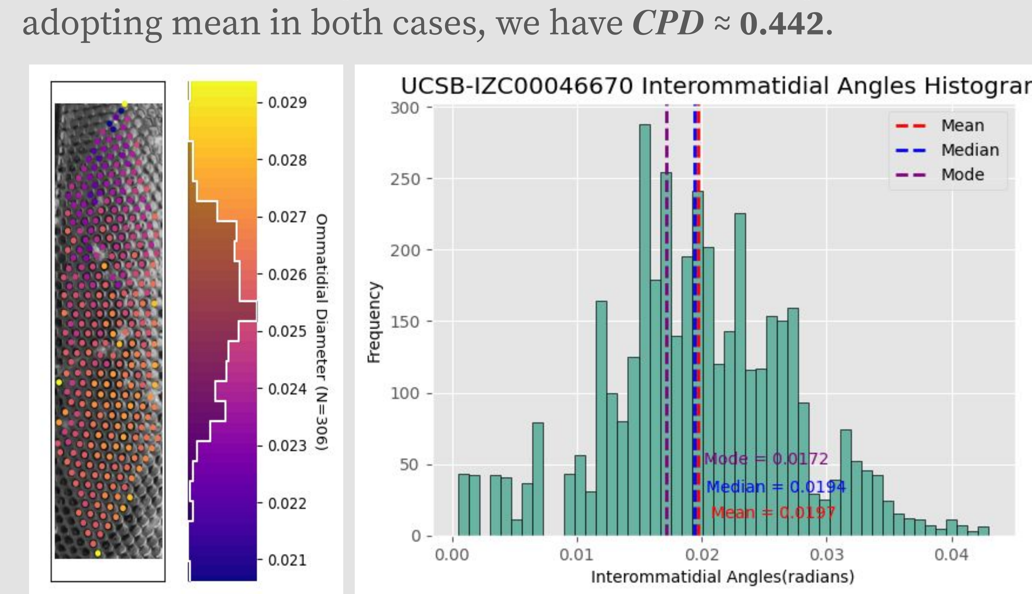

Figure 4. Visualization of Ommatidia Diameter and Interommatidial Angle Measurements for a Bee Specimen

At this stage, we gather adequate data to explore the correlation between visual acuity and the sex of bees. Our study focuses on visual acuity difference between the two primary genders, male and female, within the Apidae family, which is the most prevalent bee family in our dataset. Then, we select bees with a **scientific name** that occurs at least 3 times and visualize their corresponding visual acuity parameters below.

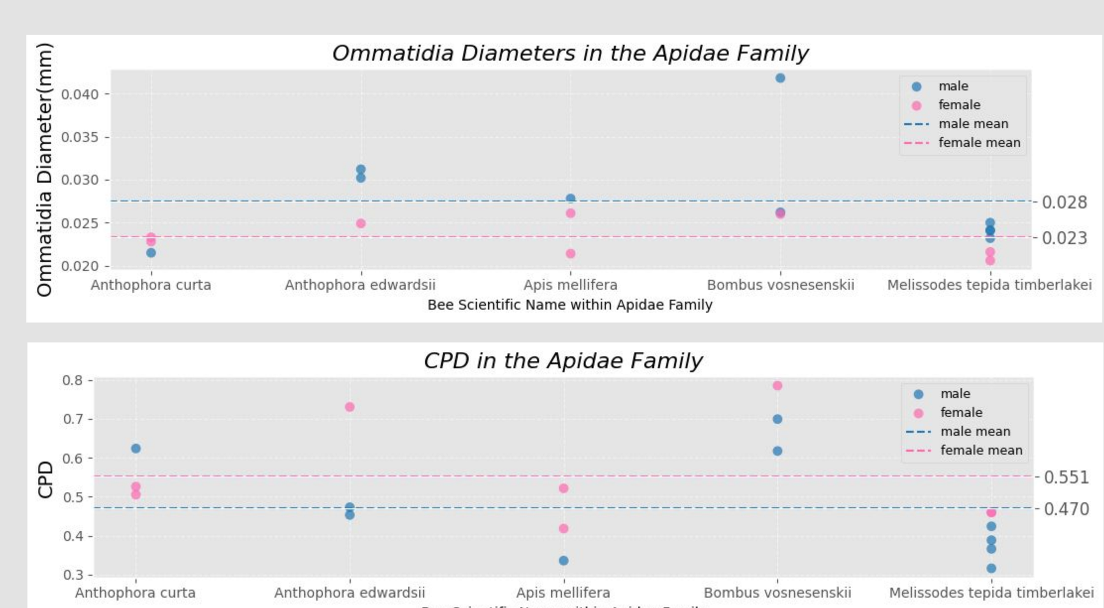

Figure 5. Scatterplots of CPD and Sample Diameter among Bee Specimens with Sex Labelings in the *Apidae* Family

Summary of findings

By examining the initial results in the *Apidae* family, we see that

- Our pipeline and algorithms can produce consistent and meaningful visual results for the biological study
- Male Bees have larger D but female bees possess better CPD to discern small details
- Male bees mostly stays in the hive and mates with the queen; larger D makes them more **sensitive in low light conditions**
- Female bees usually leave the hive to collect pollen and nectar; better CPD helps them navigate in the complex environment and interact with different objects

However, we encountered some **limitations** within our dataset:

- Some images lacking focus on eyes, hindering the 2D ODA
- Potential inconsistent results for ϕ since we can only analyze two cross section of the eye surface for a bee specimen
- D and ϕ involves 3D geometric features which are hard to capture from 2D images

Above limitations may lead to unpredictable and imprecise measurements. To ensure the accuracy of the collected data, we explored the effect of **automation** on data quality and found that

- Fine tuning a state of the art image segmentation model does not create good quality masks for rigorous contour analysis
- It's best to keep the pipeline interactive so that users can input helpful prompts to the model and handle special cases

Future work

Our project represents an initial foray into utilizing 2D images for investigating the visual acuity of bees. Initial results indicate that our pipeline can generate meaningful data on visual acuity when supplied with high-quality photographs of bee eyes. Thus, we intend to expand our research through the following approaches:

Enhancing pipeline reliability and incorporating 3D features:

- Generating high-res 2D images focused on bee eyes
- Developing a methodology to extract the surface of the bee's eyes from a **3D bee model**
- Establishing a new pipeline capable of extracting eye's internal structure from a **3D image** of a bee's head, such as μ-CT scans

Expanding the investigation of visual acuity

- Studying the correlation between visual acuity and **sociality**

References and Acknowledgments

[1] Currea, J.P., Sondhi, Y., Kawahara, A.Y. et al. Measuring compound eye optics with microscope and microCT images. Commun Biol 6, 246 (2023).

Use the QR code to access our codes