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INSECT VISION: SEGMENTATION TO SIMULATIONS

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Summary: Animals see the world through their eyes, and if the anatomical structure of an eye can be determined, then optical ray-tracing can be used to predict its visual performance. This study utilized microtomography to image the preserved eyes of a variety of insects, and after segmenting the optical structures, the volumes and surfaces were used in simulations to quantify the animal's visual capabilities. This presentation will elaborate on each step of this process, and in particular focus on different methods to simulate and quantify vision.

1. INTRODUCTION

Other animals possess very different eyes to our own, and it most cases, it is not straightforward to understand how they see the world. To study an animal's behaviour and interactions with an environment, it is necessary to know details of its visual perception. For instance, in a human eye the high density of receptors provides increased resolution in the fovea, and consequently, tasks which require acute vision, such reading this sentence, are best performed when the fovea is used. However, the resolution (and also the sensitivity) of other animals' vision typically have different topologies across their visual fields.

In this project, we are studying insect eyes (which provide a very different visual world to our own) to understand the sensory input they provide for visually guided flight control and navigation. Most insect's actually have five eyes of two types: firstly, three simple eyes in which light is focused through a single lens onto a retina of many receptors, and secondly, two compound eyes which contain many individual facet lenses, each focusing light onto a single receptive unit [1]. The visual fields of these five eyes usually overlap, creating a relatively complicated visual-representation of the world [2]. We are using X-ray microtomography and optical simulations as a new approach to quantify the visual specializations of different insects' eyes (Fig. 1A,B,C). These techniques are used to measure the parameters defining the resolution and sensitivity across each eye type. The measurements can also be projected back onto an image, providing a relatable representation of how it would be viewed by the insect.

2. EXPERIMENTAL METHOD

Insect eye were imaged for this project at a variety of facilities, including the I13-2 beamline at the Diamond Light Source, the TOMCAT beamline at the Swiss Light Source, and the 4DImagingLab at Lund University. Segmentation of the imaged anatomy was performed using Amira (FEI), where manual and semi-automated tools are used to label the structure of lenses, light guides and receptors. Segmented data was exported from Amira in volumetric and surface formats and visual simulation and quantification are performed using Matlab scripts.

3. RESULTS

To perform accurate optical simulations, it was necessary to quantify the shape of the primary structures of an insect eye. For simple eyes, this required the segmentation of a lens, a pigmented iris, and the gross retinal volume. For compound eyes, we initially segmented gross volumes comprising the entire lens structure, the underlying light guides and the retina. The size of several individual lenses were also measured at the volumes surface and interpolated across the eye, and we have also developed a semi-automated approach to locating individual light guides [3]. Identifying the dimensions of individual receptors within each retina is challenging as they have low absorption contrast against the surrounding material.

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Having segmented the data, it is then possible to perform optical simulations [4]. For simple eyes, where all refractive interfaces have been segmented, ray-racing can be conducted using the principles of geometric optics. This traces the path of light from a point in the world, through the lens, and onto the retina. Ray-tracing allows the field of view of the eye can be determined, and the resulting point spread functions (PSF) can be used to determine the optical intensity and cut-off frequency when light from different points in the world is imaged onto the retina. In the future, we aim to individually segment the receptors in the retina and calculate absorption within these directly, providing a direct measurement of the retinal sampling.

Our initial analysis of compound eyes has not utilized ray-tracing directly, but made calculations based on geometric principles of their function [5]. Lines can be projected from each lenses surface along its normal vector to identify its viewing direction (Fig. 1D), and the angle between vectors allows the sampling resolution to be calculated (Fig. 1E). Furthermore, the size of each lens indicates the angle from which it will focus light onto its receptor. To completely simulate vision in compound eyes we now need to segment the location of each light guide underlying the lenses, which are the individual apertures for each receptor.

When the resolution and sensitivity of an eye is known in relation to its visual field, this information can be used to simulate the insect's vision. The simulation can be as simple as locally discretizing an image to represent the sampling resolution of a compound eye (Fig. 1F,G), but can be extended by filtering the image and modulating its intensity to represent the influence of the optics on sensitivity and resolution. Both of these methods highlight how an insect eye views the visual world in a different manner to ourselves.

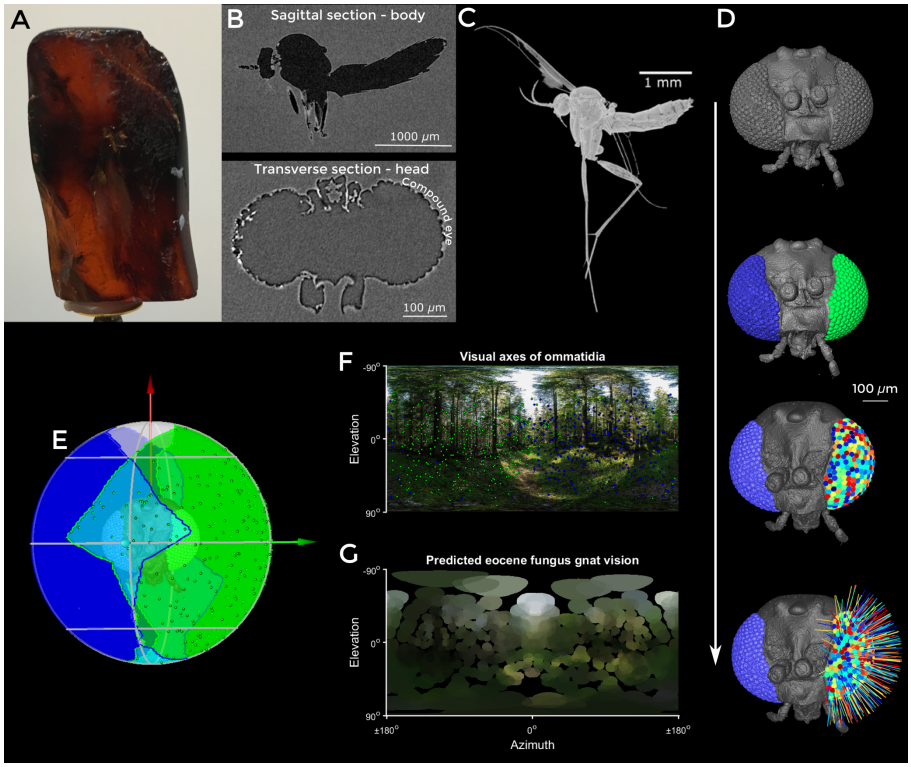

Figure 1: Quantifying the vision of a fungus gnat preserved in an opaque piece of Baltic amber (A). Microtomography shows the insects form (B & C). After fitting a surface around the cuticle, each facet of its compound eye can be segmented to find the surface of each facet and their optical axes (D). These axes define the field of view of the gnat's eyes (E), and can be projected onto an image (F) to simulate the gnat's vision of that scene. This study was conducted in collaboration with Stephen Hall and Johan Gren.

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