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Development of an open source pupilometer for testing melanopsin responses

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Background

The intrinsically-photosensitive melanopsin-expressing retinal ganglion cells are of interest for several reasons. Quantifying melanopsin function with the post-illumination pupil response (PIPR) is of potential use in clinical research.

Moreover, a cheap and versatile pupilometer may have application in a range of research settings, neurological and ophthalmology practice, and in many primary care settings such as ambulances, emergency departments and family practice.

Standard video pupilometry uses infrared (IR) video of the pupil, lights to stimulate pupil constriction, and software to measure pupil size from the video. The PIPR additionally requires stimulating blue light of high luminance (> 100 mcdm^{-2}). Portable pupilometers cost thousands of dollars and do not have capability to test PIPR, while PIPR is usually tested with non-portable electrophysiology equipment costing many tens of thousands of dollars.

Proposal

Can an affordable pupilometer be created using widely available technology, with the required capabilities to test melanopsin function as well as common clinical scenarios?

Methods

We identified the core requirements for versatile pupil testing in a wide range of scenarios, such as anisocoria, refractive surgery planning, testing pupils after head injury, quantifying a relative afferent pupil defect (RAPD), and potentially testing quadrants individually (what could be termed multifocal pupilometry).

These requirements were:

- A close fitting goggle to eliminate ambient light and provide illumination from a large visual angle
- An IR video camera with sufficient optical quality to allow filming of the pupil at high spatial and temporal resolution in both light and dark conditions
- Illumination of high intensity, fine control, all colours, and potentially directional illumination (e.g. testing sectors of the visual field)
- Portability, connecting to a computer or smartphone wirelessly, with a degree of internal data processing

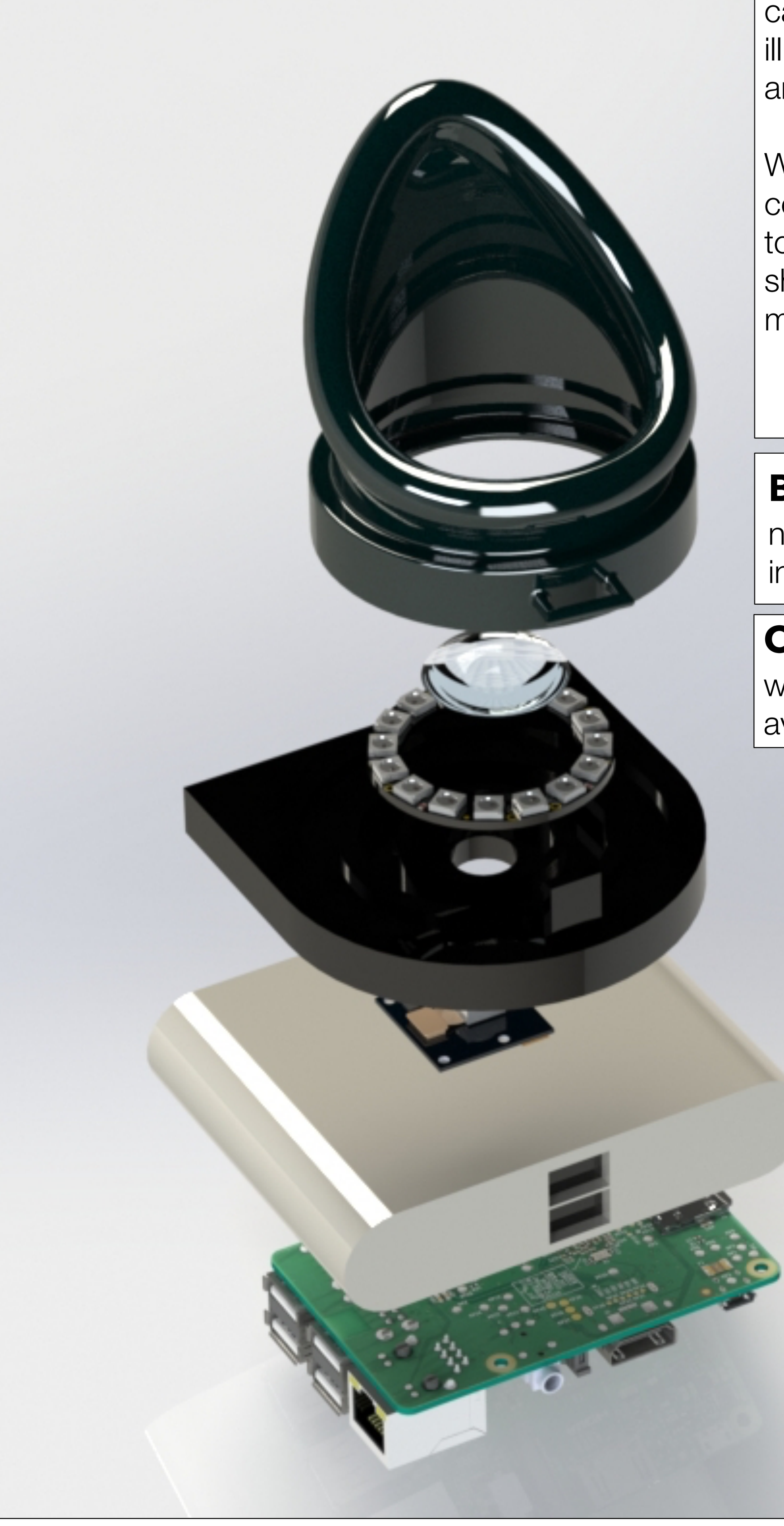
We investigated the cheapest, widely-available components that would meet these requirements.

The design, software, and all early findings were made freely available on an open source directory in the spirit of collaboration.

https://github.com/kaiwhata/openpupil GitHub

Hardware

Figure 1 Exploded view of device



Goggle (housing) This functions to exclude ambient light, position the camera at the correct distance in front of the eye, and diffuse incident light to illuminate the whole field. It must be comfortable, ergonomic (fitting most orbits), and hygienic (easy to clean).

We have tested a range of designs and 3D printing materials. Further prototyping continues with flexible, cleanable materials that can diffuse light. Our intention is to provide all designs for free at 3D printing service and marketplace shapeways.com, allowing interested users to create the parts easily in the ideal materials at cost (approximately USD $10.00).

www.shapeways.com/shops/openpupil shapeways

Background illumination Two super-bright 5 mm IR (940 nm) light emitting diodes (LEDs, cost USD $0.75 each) were housed in the goggle, providing background IR illumination of the pupil.

Optics This biconvex lens functions to bring the camera into focus at a short working distance. These 25 mm plastic lenses of 22 D power are widely available for Google Cardboard virtual reality sets, at a cost < USD $0.40.

Stimulation This ring of 16 NeoPixel individually controllable red, green and blue LEDs is widely available for USD $10.00.

LED Colour	Wavelength (nm)	Luminous intensity (mcd)
Red	620-630	550-700
Green	515-530	1100-1400
Blue	465-475	200-400

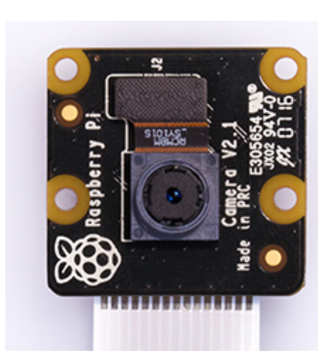
Each NeoPixel in the ring can control red, green and blue light individually with 255 levels of brightness. The maximal luminance of blue light is adequate to generate a robust PIPR. The ring arrangement allows for sectoral testing of the visual field.

Figure 2 Commercial images of 16 NeoPixel ring showing size, function

Power source This battery pack is rechargeable with a simple USB cable and provides two power sources of 5 V, one 1 A supply for the stimulation LEDs and one 2 A supply for the Raspberry Pi and downstream devices. Batteries of this type are available with 10,000 mAh storage for USD $39.95

Video camera This Raspberry Pi PiNoIR v2 video camera Is available for USD ~$25.00.

It has an 8 megapixel sensor and detects infrared (IR). We placed a photographic high pass IR filter over the camera and were able to exclude visible light while seeing the pupil in crisp detail. The camera has auto-focus and auto-exposure firmware that may be disabled. Frame rate is usually 25 Hz.



Micro-processor This Raspberry Pi 2 model B+ board is available for USD ~$38.00. It contains a 900 MHz quad-core central processing unit (CPU) with 1 GB random access memory (RAM), multiple ports and interfaces. We intend to use the Raspberry Pi 3 with wireless interface and Bluetooth in upcoming prototypes.

Although other more powerful micro-computers are available, this is the cheapest board with the necessary specifications for image processing, data transfer and video display simultaneously. Software was written for the operation of the hardware and analysis of the collected video images using C++ programming on the Raspbian open source operating system.

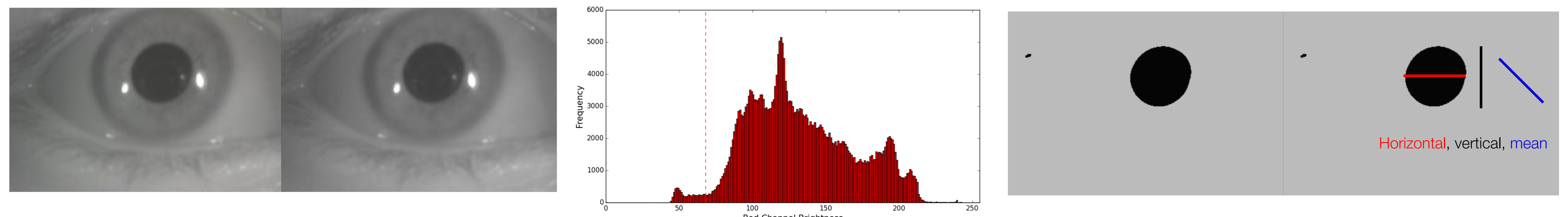
Total hardware costs – some assembly required

The plans to replicate this device are available open source for free access and collaborative refinement. The components cost a total of approximately USD $140.00 plus a minor degree of circuit board connection and assembly with soldering and BluTack and a container. We hope that this hardware gains increasing use in research projects internationally.

Figure 3 Images of the stimulation LEDs in use

Software

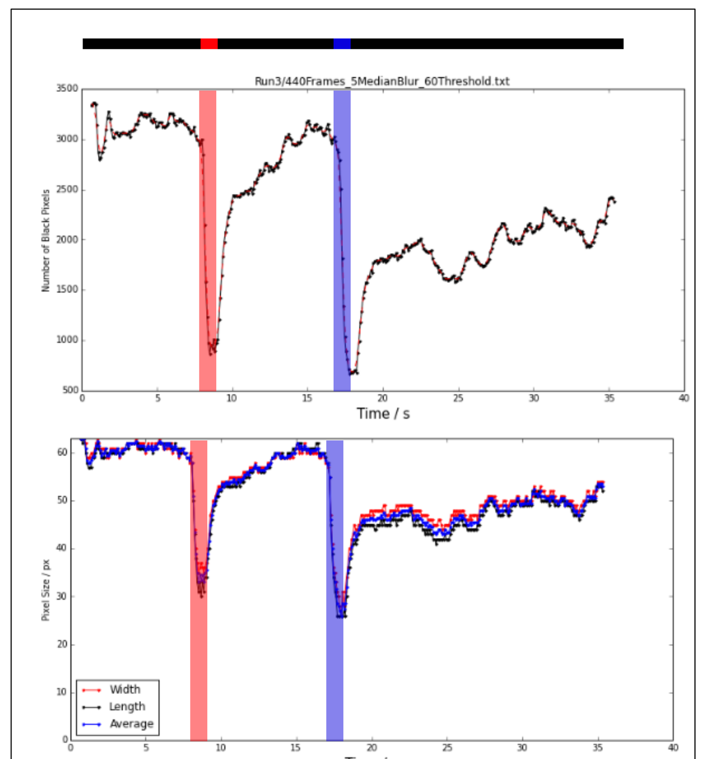
Frame-by-frame image processing software was written using C++ language to run on the Raspbian operating system. The red channel was isolated, and histograms showed a peak of darkest pixels representing the pupil (Figure 4). Trial of numerous dynamic and static and adjusted threshold settings led to a static threshold at the luminance of the 6000th darkest pupil (after 10 s dark adaptation) to estimate the pupil signal. This led to a binary image for all subsequent video frames, from which pupil area (pixels), and vertical and horizontal and mean pupil diameter were calculated.



Unprocessed RGB | Red channel | Histogram, threshold shown | Binary image | Pupil diameter

Figure 4 showing the sequential processing of one frame by one iteration of the program.

Experimentation with increasing contrast was found to reduce signal-to-noise ratio, median blur reduced single-pixel noise but slowed performance excessively, and the Canny edge-finding and Hough circle-finding algorithms resulted in errors and increased noise from reflections on the cornea (Figure 5).



Increased contrast | Median blur | Hough algorithm

Figure 5 shows discarded processing techniques

Figure 6 shows the pupil area above and pupil diameter below in response to 9 s darkness, then a bright red flash of 1 s, then 9 s darkness, then a bright blue flash of 1 s followed by darkness for 18 s. The PIPR to blue light is shown.

The program illustrated in figure 4 was used to record from volunteers in the laboratory, and a robust PIPR could be demonstrated (Figure 6). Processing time (using the RPi 2B+) board allows for real time measurement and display of pupil size at around 20 Hz, although raw video at a faster frame rate could be also be streamed for measurement in retrospect.

Conclusions

The proliferation of cheap components, powerful and versatile microprocessors, and 3D printers enables the development of new clinical and research tools at low cost.

Future directions

- Evaluation and refinement of the goggle design to improve ergonomics and hygiene
- Calibration of pupil size measures for accuracy and stimulation LED photometry for safety
- Validation studies comparing to existing pupilometry devices
- Development of phone application to enhance the portability and usability of the device
- Development of cloud based data storage and analysis

MedTech CoRE
Seed grant application In process

References

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Capital Vision Research

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A full list of references, our production files and current program codes, available at:

https://github.com/kaiwhata/openpupil

Contacts

To inquire or contribute, or to obtain one of these devices for your own research, please contact us.

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