PACE: Pupillometric Analysis of Cognitive Effort

Maxx Berry[1], Evan Braley[1], Lauren Broadbent[1], Gordon Chau[1], Ariel Sousa[1], Max Vivino[1]
Sanghee Moon (Sponsor)[2], Soomin Kwon (Graduate Assistant)[2], Lisa Henry (Advisor)[1]
1. Department of Computer Science, University of New Hampshire; 2. Department of Kinesiology, University of New Hampshire

MOVE Lab
MOtion in Virtual Experience

University of New Hampshire

Pupil dilation reliably tracks **cognitive load** during neuropsychological testing. This can be done **affordably using standard webcams**, not just expensive eye-tracking hardware.

INTRODUCTION

- **PACE** investigates pupil dilation during neuropsychological tests as a cognitive load indicator for clinical pre-screening
- Fall semester (2025): Tobii Pro Glasses 3 (Fig 1) + PEBL tests (Fig 3)
- Spring semester (2026): Insta360 Link 2 webcam (Fig 2) + PEBL BCST (Fig 3)
- Long-term goal: Affordable, real-time cognitive-load monitoring using low-cost eye-tracking

Fig 1: Tobii Pro Glasses 3

Fig 2: Insta360 webcam

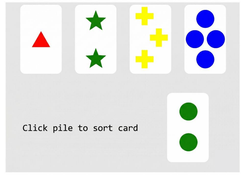

Fig 3: PEBL BCST Test

REQUIREMENTS

Functional Requirements

- Tobii Pro Glasses 3/Insta360 camera track and capture pupil data during testing
- PEBL tests induce varying cognitive load
- Raw pupil data is pre-processed for downstream calculations
- ML model achieves $R^2 \geq 0.60$
- Program accurately estimates the Index of Pupillary Activity (IPA) score

Non-Functional Requirements

- System is low-cost and scalable
- Results are easily interpretable
- Lighting, glare, and shadows are minimized during testing

DESIGN

- **SOP:** Questionnaire, setup, test administration, file organization; updated for webcam
- **Pre-test:** Demographics and factors affecting pupil dilation
- **Testing:** Quiet environment, 30s baseline dilation before PEBL test
- **Tobii Pipeline:** Filtered in Tobii Pro Lab → CSV export → Python analysis (Fig 4)
- **Webcam Pipeline:** MP4 processed via OpenCV + PyPupilEXT, reformatted for existing IPA code (Fig 5)

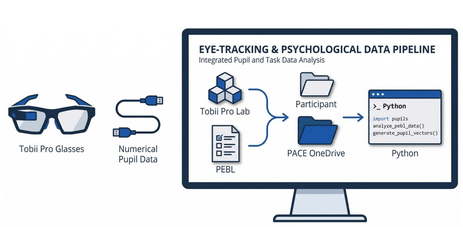

Fig 4: Tobii Pro Data Pipeline

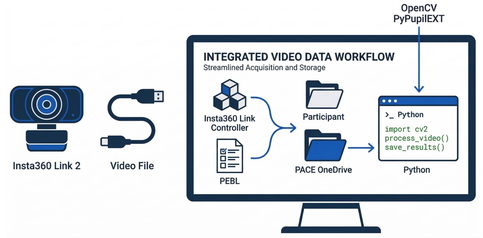

Fig 5: Webcam Data Pipeline

IMPLEMENTATION

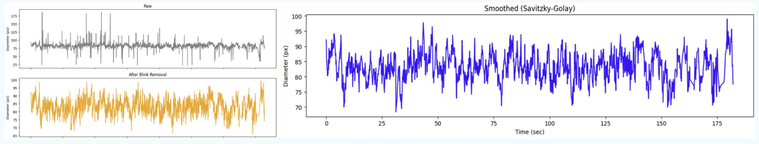

Fig 6: Webcam Pupil Preprocessing

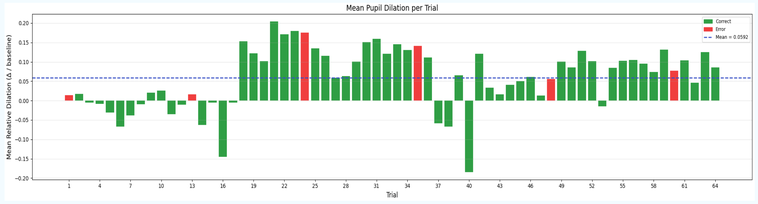

Fig 7: Trial-level Mean Pupil Dilation by Response Outcome

System Implementation

- Pupil extraction using OpenCV / PyPupilEXT
- Random Forest trained on Tobii Pro features for cognitive prediction
- Wavelet-based IPA

Signal Processing

- Noise reduction (blink removal, Savitzky-Golay smoothing filter) (Fig 6)
- Standardized frequency range (0–1 Hz) (Fig 10)
- Improved signal isolation from eye region

Key Output

- Model performance: $R^2 = 0.64$ (Fig 9) and IPA captures cognitive load trends over time

RESULTS

Key Findings

- Detected rapid pupil fluctuation and estimated dilation spikes
- IPA reflects changes in task difficulty

Observed Trends

- Higher IPA values correspond to increased effort (Fig 10)
- Time-on-Task reduces noise and reveals fatigue patterns (Fig 11)
- Signal quality preprocessing reduces eyelid/skin interference (Fig 8)

Implications

- Supports feasibility of low cost-eye-tracking enabling broader accessibility for cognitive assessment and potential for real-time applications

<0.25 Hz	• Low cognitive effort
0.25-0.4 Hz	• Moderate cognitive activity
0.40-0.65 Hz	• High sustained cognitive effort
>0.65 Hz	• Peaking workload, maximum effort

Fig 10: Standardized Cognitive-effort Frequency Range

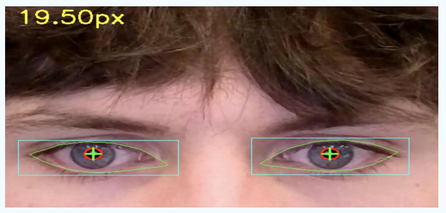

Fig 8: Real-time Elliptical Pupil and Diameter Estimation

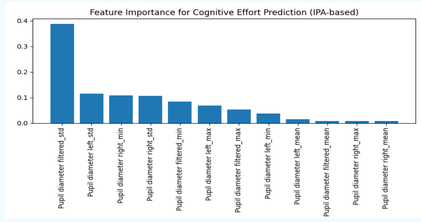

Fig 9: Feature Importance for Random Forest Model

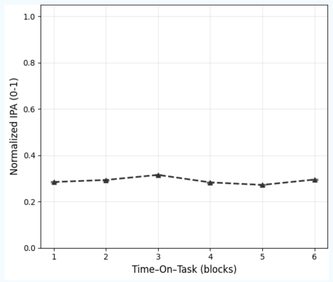

Fig 11: Time-On-Task Blocks Revealing Changes in IPA

EVALUATIONS & CONCLUSIONS

Conclusion

- Pupil dilation is a reliable indicator of cognitive load
- Webcam-based approach achieved comparable performance
- Demonstrates feasibility of a low-cost alternative to traditional eye-tracking

Limitations

- Lighting sensitivity (need controlled environment)
- Reduced accuracy for darker irises

Future Work

- Improve model accuracy
- Develop real-time application for pipeline
- Expand testing across diverse populations