Medusa3D: The Watchful Eye Freezing Illegitimate Users in Virtual Reality Interactions

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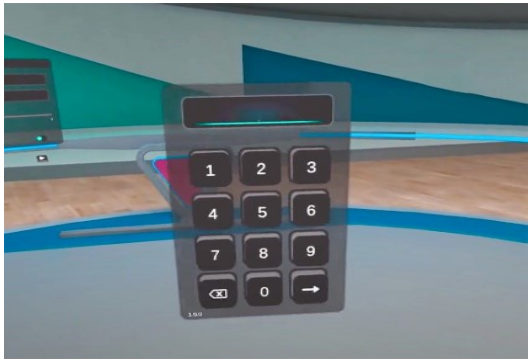
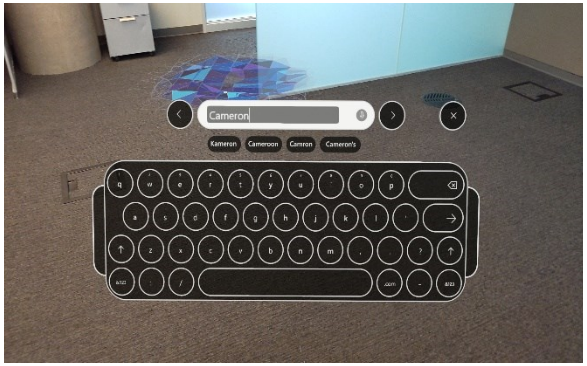
Background

PIN / Password in VR





Shoulder-surfing Attack

Background

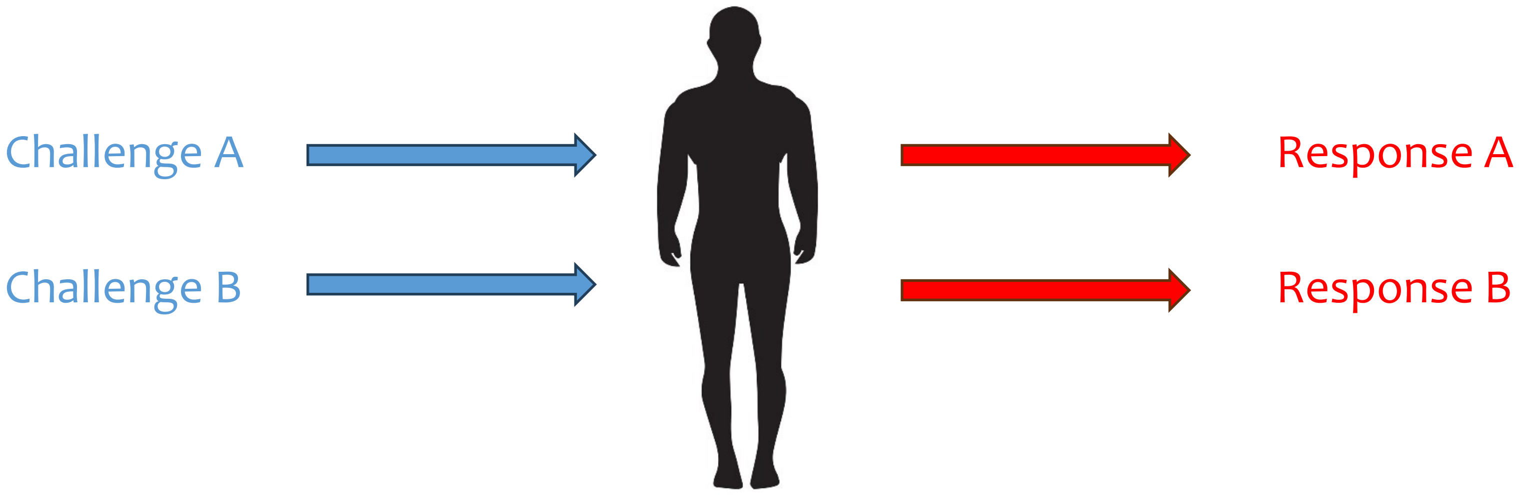
Static Biometric

Vulnerable to **data leakage** and **replay attack**

Once stolen -> unrecoverable

Background

Active Biometric



Response = H (Challenge)

Challenge-Response Method

Biometric is human’s response **pattern** to challenge,
but not specific challenge or response.

Motivation

> *Reflexive eye movement is an activity that is driven by visual stimulation but does not require volitional control.*

- R John Leigh and David S Zee. The neurology of eye movements. Contemporary Neurology

- **VR headsets that already include integrated eye tracker**

Primax Crystal

PlayStation VR2

HP Reverb G2

Pico Neo 3 Pro Eye

HTC Vive Pro Eye

- **Can we use reflexive eye responses as biometric?**

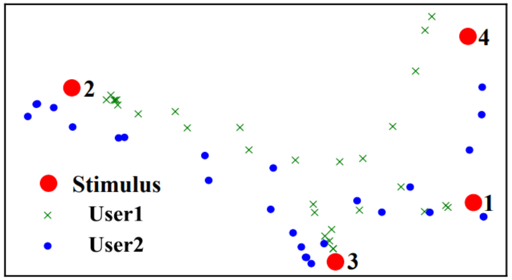
Preliminary Study

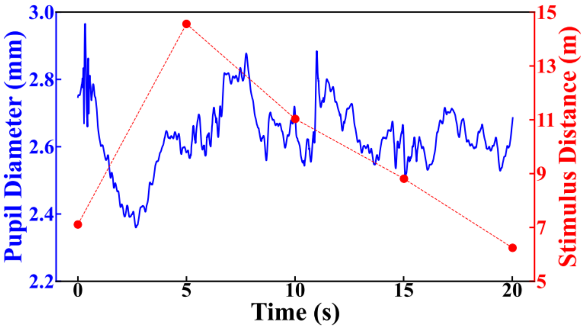
❖ **What eye responses are reflexive?**

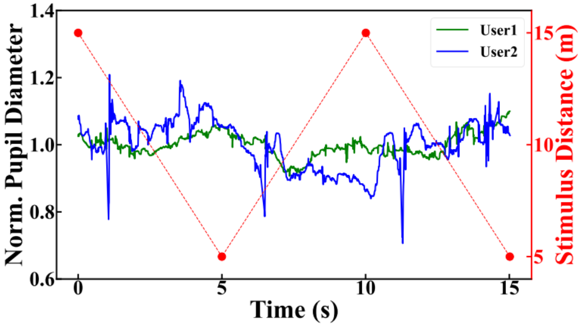
- Reflexive saccade
- Pupil diameter change

❖ **How to elicit the reflexive responses?**

- When a noticeable change occurs in the field of view
- When focused object changes its depth



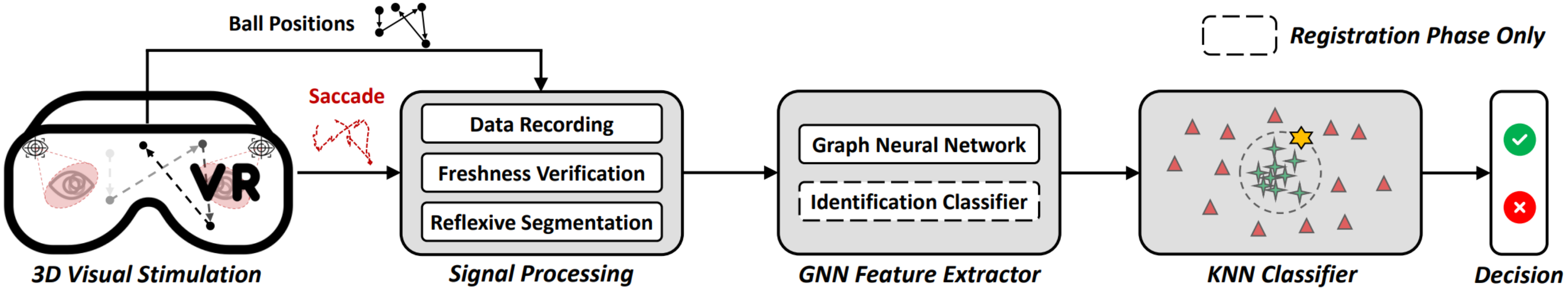




System Design

❖ Overview

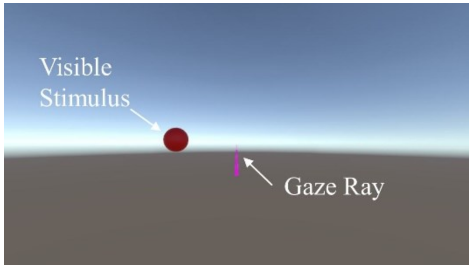
- Visual stimulation
- Signal processing
- Feature extraction & Authentication



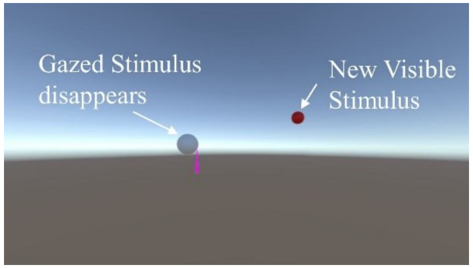
System Design

❖ Visual Stimulation Design

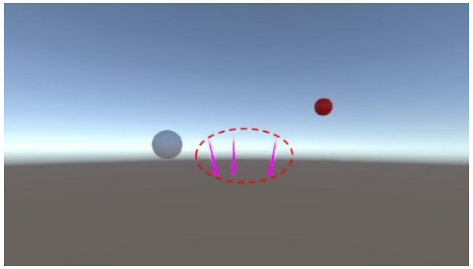
- **Salient change:** *elicit reflexive saccades.*
- **Variable depth:** *elicit pupil diameter changes.*
- **Unpredictability:** *exclude the interference from memory.*



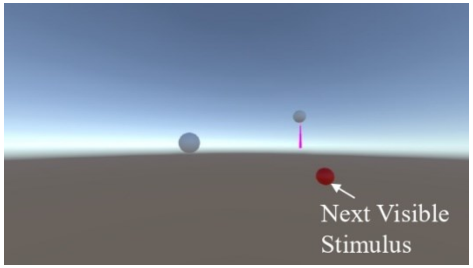
(a) Stim. appears in FOV



(b) Gaze intersects stim.



(c) Saccades catch stim.



(d) New stim. is gazed.

System Design

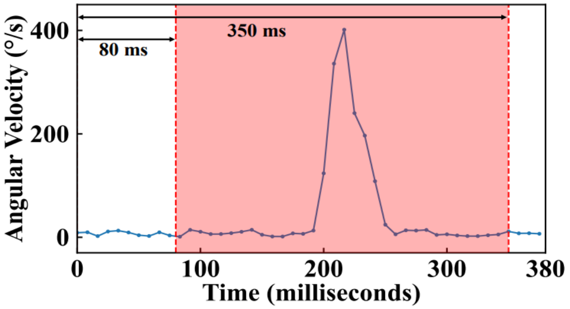
❖ Signal Processing

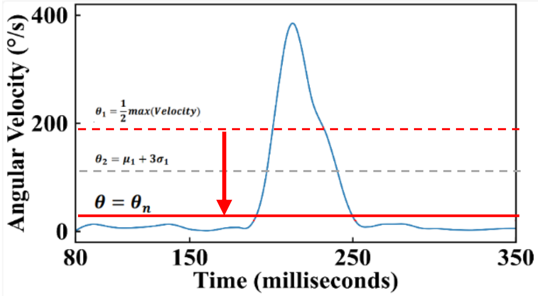
- Reflexive saccades segmentation

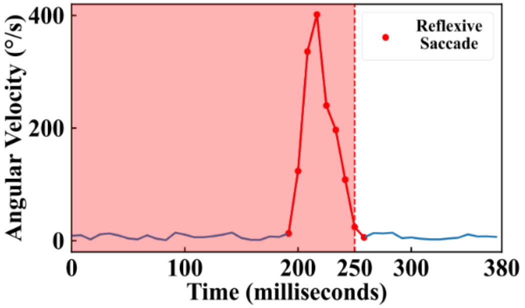
  ○ *Determine the time interval reflexive saccades may occur.*

  ○ *Employ iteration method to adaptively search the threshold.*

  ○ *Verify the reflexivity of saccades extracted.*







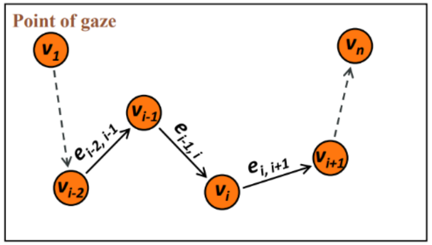
System Design

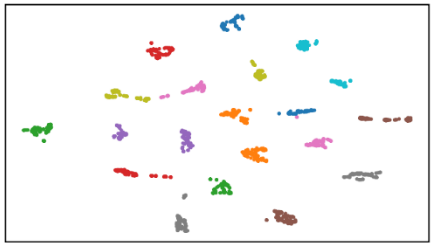
❖ Feature Extraction & Authentication

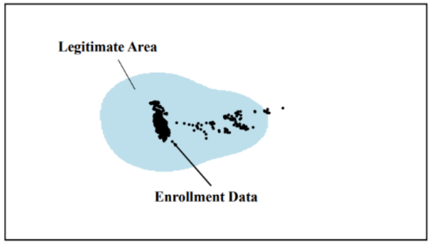
- Graph design
  - *We embed the spatial information of reflexive saccades into a graph.*

- GNN network design
  - *We design a graph-oriented network that can classify the users' feature*

- KNN classifier
  - *With the feature extracted, a user-specific KNN model is selected that can package legitimate user samples.*







Evaluation

❖ Set-up

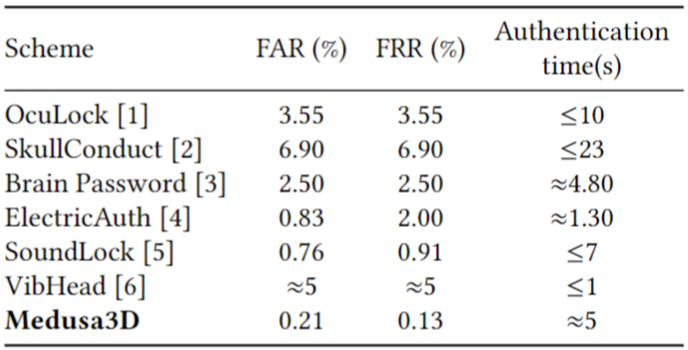
- Device:
    - *HTC VIVE Pro Eye*

- Threat model:
    - *Zero-effort attack*
    - *Replay attack*
    - *Mimicry attack*
- Participants:
    - *25 (20 users + 5 attackers)*
    - *Various in demography and background*
- Evaluation metrics:
    - *FAR: False Acceptance Rate*
    - *FRR: False Reject Rate*

Evaluation

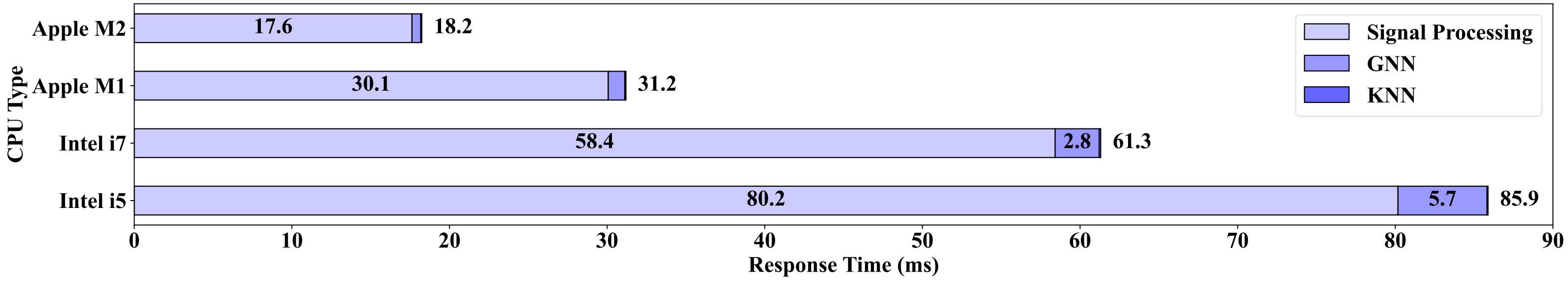
❖ Overall Performance

- Overall 0.21% FAR and 0.13% FRR
- Time required for authentication is about 5 s.



Scheme	FAR (%)	FRR (%)	Authentication time(s)
OcuLock [1]	3.55	3.55	≤10
SkullConduct [2]	6.90	6.90	≤23
Brain Password [3]	2.50	2.50	≈4.80
ElectricAuth [4]	0.83	2.00	≈1.30
SoundLock [5]	0.76	0.91	≤7
VibHead [6]	≈5	≈5	≤1
Medusa3D	0.21	0.13	≈5

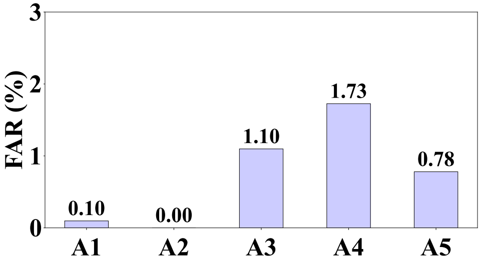
[1] Luo et al. 2020. OcuLock. NDSS 2020.
[2] Schneegass et al. 2016. SkullConduct. CHI 2016.
[3] Lin et al. 2018. Brain Password. MobiSys 2018.
[4] Chen et al. 2021. ElectricAuth. CHI 2021.
[5] Zhu et al. 2023. SoundLock. NDSS 2023.
[6] Li et al. 2024. Vibhead. TOSN 2024.



Evaluation

❖ Zero-effort attack

- Attackers attempt to unlock the device with their own biometrics as credentials
- FAR ~ 1%



❖ Replay attack

- Attackers replay a pre-recorded eye movement response.
- Challenge is always new. Pre-recorded one cannot match the new challenge.

❖ Mimicry attack

- Attackers acquire and imitate the eye movement patterns
- Visual stimuli are random and new every time.
- Imitation is voluntary and will be excluded from the reflexive part.

Conclusion

- We propose Medusa3D, a challenge-response authentication system for VR based on reflexive eye responses.

- Medusa3D can utilize active biometric for authentication on users while keep safe against attackers.

- Future work will primarily focus on enhancing the system's robustness for long-term use.

Thanks for your attention!
Q&A

I am actively looking for Ph.D. position starting 2025. Feel free to contact me if you have any relevant information.

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Personal Website