Effects of Pupil Swim on Eye-Tracking in Virtual Reality

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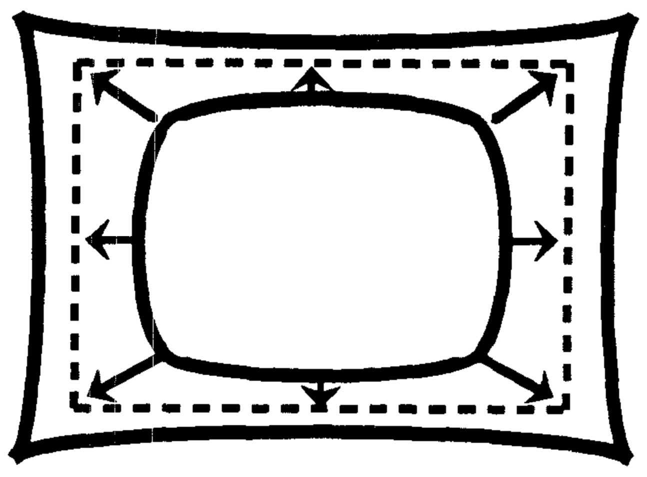
Research Questions

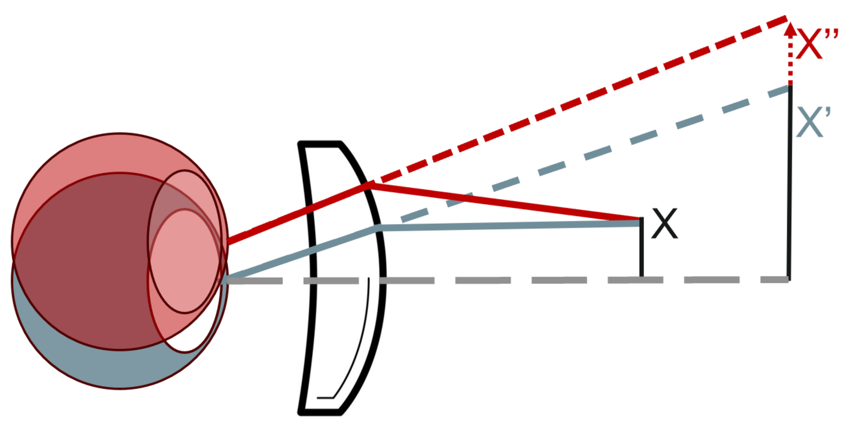
- How much does pupil swim shift the virtual environment in the Varjo XR-3?
- Is the eye-tracking data in the Varjo XR-3 suitable for implementing a dynamic predistortion solution?

Background

- Pupil swim is the change of image quality as the eye moves or rotates within the eye-box. [1]
- Head-mounted displays (HMDs) often have a pin-cushion distortion in their strong lenses. [2]
- These distortions are corrected by warping the image on the display by applying a barrel distortion known as predistortions. [2]



- The predistortions are derived from the optical center of the lens. However, the distortion form the lens changes as a function of position of the eye and rotation of gaze.[3]
- For example: when looking left, virtual objects shift to the left.[3]



- Solutions have included implementing eye-tracking to dynamically alter the predistortions. [3,4]
- To implement such solutions, eye-tracking must be tested in off-the-shelf HMDs. [3,4]

Hypotheses

- As the viewing angle reaches the extrema of the Varjo XR-3's field-of-view, the virtual targets will shift towards the edge of the field-of-view.
- As the convergence angle increases, the virtual target shift will increase nasally.
- Eye tracking data will report where the eye is looking in the field of view and not compensate for pupil swim distortions.

Acknowledgments

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References

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2. Watson, B. A., & Hodges, L. F. (1995).
3. Rui C., Zhao L., Hou T., Liang J., Wang C. (2023)
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Methods

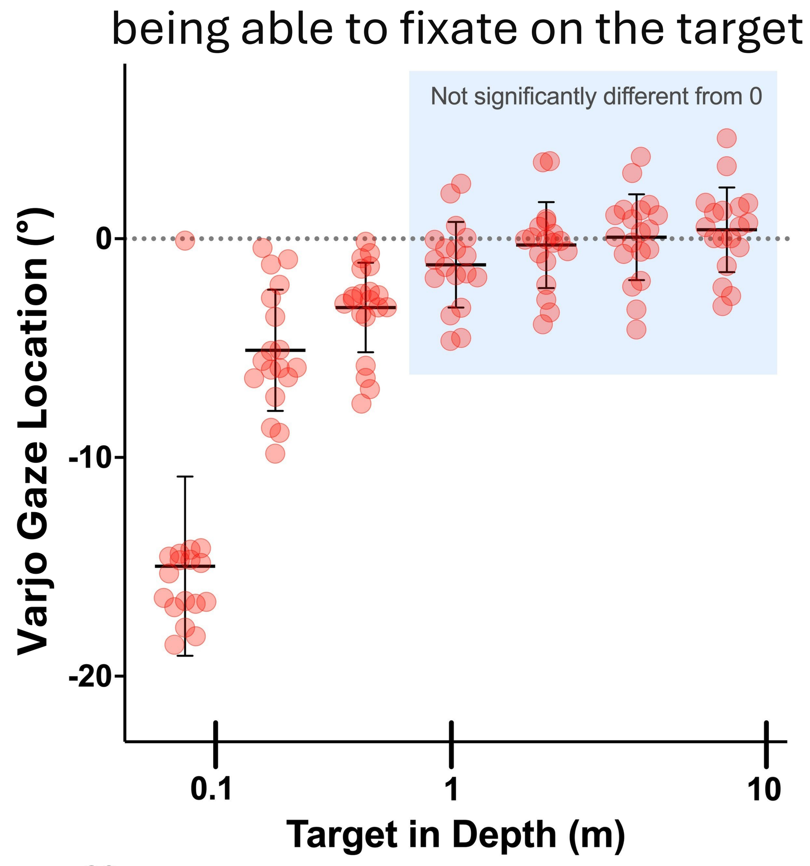
Varjo XR-3
200Hz Eye-tracker
Aspherical Lenses

- Participants (***N = 10***) were asked to monocularly (right-eye) fixate on targets of 1° visual angle within a Varjo XR-3 and then respond with a controller.
- The targets are presented in a totally black environment as uniformly lit, white discs facing the participants.
- 3 target categories; unique targets are repeated once:
  - Targets centered exactly between the eyes at distances 0.1m, 0.25m, 0.5m, 1m, 2m, 4m, and 8m
  - Targets at 8m distance spanning the participant's horizontal field-of-view from angles -25° through 60° in 5° increments
  - Targets at 0.1m distance spanning the participant's horizontal field-of-view from angles -15° through 55° in 5° increments
- 3 participant response types to targets:
  1) Able to fixate
  2) Unable to find
  3) Able to find but unable to fixate
- Participants had their HMD centered vertically to eye-height and horizontally to the midpoint between the eyes.
- Eye-tracking is done by ray casting from the gaze starting point (the right-eye) at the angle provided by the eye-tracker to return a point in Unity space.

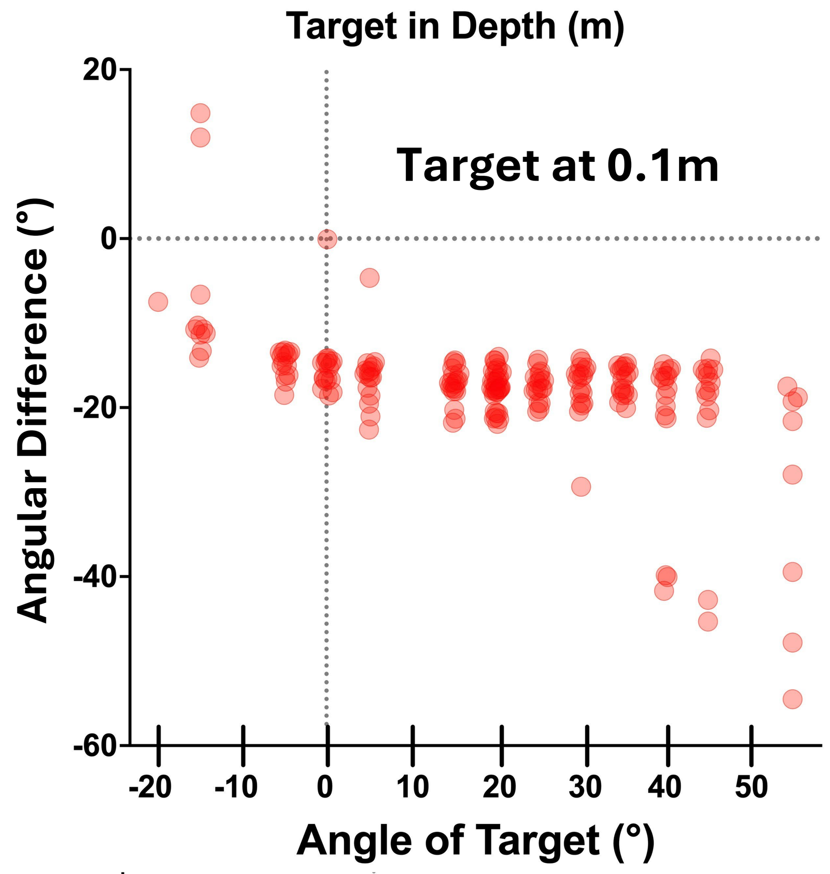
Eye-tracking on the Varjo XR-3 does not report accurate fixation locations at or below 0.5m!

Results

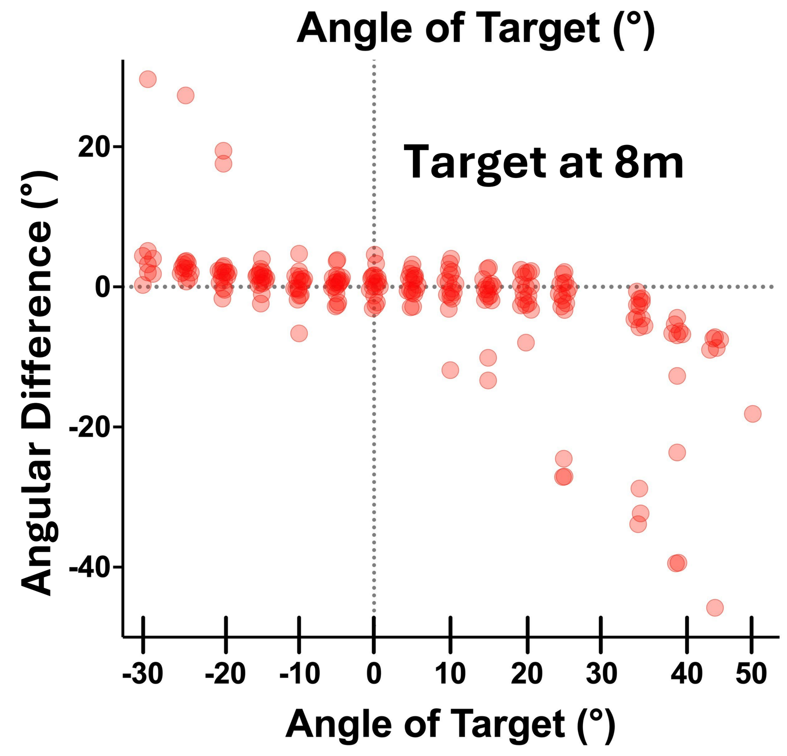
- The amount of screen space unable to be fixated on is calculated from the smallest degree that subjects are unable to find the target subtracted by the smallest degree that subjects are able to find, but unable to fixate on the target.
  - Any subjects that fail to report either not finding the target (response 2) or not being able to fixate on the target (response 3) across all trials are excluded.



- When converging on targets at 0.5m or closer, eye-tracking data shows the location of fixation is significantly different from the 0° location the subject is actually fixating.
- The direction of bias is in the same direction of the distortion expected from pupil swim.



- All angles are significantly different from 0°.
- Eye-tracking error is not a function of target angle.
- The mean amount of screen space not able to be fixated on is 15° **(N = 1)*** in the periphery while the amount nasally is 3.33° **(N = 3)***.



- All angles are **not** significantly different from 0°, contrary to our hypothesis.
- The mean amount of screen space not able to be fixated on is 12.22° **(N = 9)*** while no participants fit the criteria to calculate nasally.

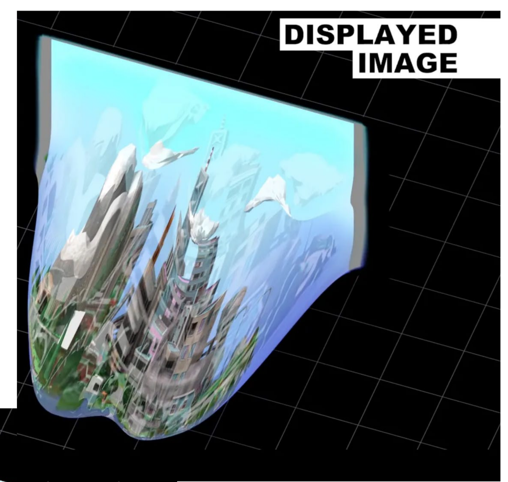
*Low N count from subjects not experiencing targets appearing outside of their field-of-view

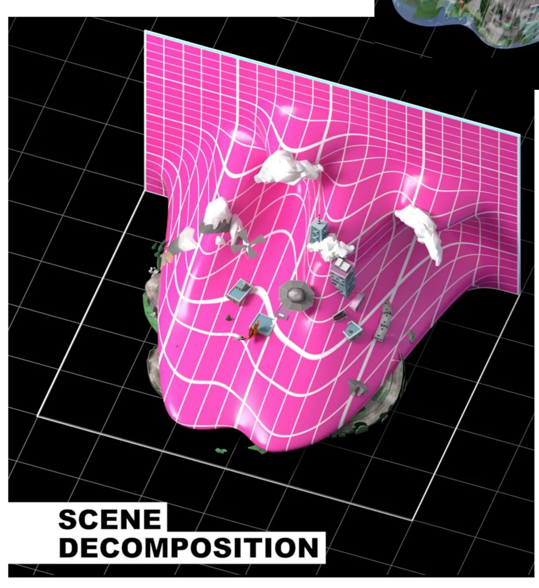
Discussion

- As convergence angle increases, the Varjo's eye-tracking becomes less accurate. Specifically, the location reported suggests the target shifts in the expected direction of the distortion induced from pupil swim.
- 0.1m eye-tracking data is inaccurate across the field-of-view.
- Participant reports reveal that pupil swim can shift targets up to 12.22° at 8m. However, eye-tracking data reports correct target fixations across the field-of-view at 8m. Where does that 12.22° go?
- At fixed distances across the user's field-of-view, error does not follow any distortion pattern as predicted.[3]
- These findings suggest software is compensating for pupil swim to some degree but does not work in all cases.
- Of the 115° of horizontal field-of-view at 8m, nearly 20° of the space is not able to be fixated on due to distortion from pupil swim.
- For Varjo XR-3 fixations at 8m, implementing a dynamic predistortion solution for pupil swim with its own eye-tracker will allow for fixations of the entire field-of-view.

Focal Surface Display [4]:

It is the same solution!





Future Directions

- Collecting similar data from other HMDs capable of eye-tracking with a focus on the difference between Fresnel, aspheric, and pancake lenses.
- Finer grain manipulations of angles and distances will give a clearer picture of where eye-tracking is most accurate.
- Implementing a dynamic predistortion akin to focal surface displays [4] serve as a lightweight and cost-effective solution to spatial pupil swim distortions.
- Phase spatial light modulators may be a robust, hardware-based solution. [5]

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