Understanding function and development of the perceptuomotor system through environment-animal interactions

Research prospectus in response to FOA NSF-24-546 · April 2025

Benjamin Scholl [1] · Jonathan Samir Matthis [2,3]

[1] University of Colorado Anshutz · [2] FreeMoCap Foundation · [3] Northeastern University

benjamin.scholl@cuanschutz.edu · jonmatthis@gmail.com

Research Overview

- Environmental energy elicits patterns of perceptual neural activity which form the basis of goal-directed motor behavior.
- The coupling between an organisms moment-to-moment perceptual input and their motor output defines the basic agent/environment Perception-Action Loop ((Warren, 2006)) which underpins goal directed behavior (such as chasing a moving target)
  - Animal moves, generate retinal optic flow
  - Retinal optic flow specifies egocentric movement relative to external objects ((Matthis et al., 2022))
  - Self-motion estimates drive locomotor state and goal ((Fajen, 2003))
  - Behavioral goals/Task ((Hayhoe & Ballard, 2005)) dictates information needed for successful behavior (which drives oculomotor behavior, e.g. gaze targeting and stabilization ((Matthis et al., 2018)))
- This Perception/Action cycle has been studied extensively in humans, but research is lacks neural grounding
- Similarly, the neural basis of oculomotor control and low level visual perception well mapped in various animal models, but behavior often extremely impoverished and so lack ecological validity.
- This project seeks to under stand the functional mappings between gaze, locomotion, and behavior
- We co-develop our research plan in parallel to a novel experimental apparatus representing our best approximation of the impossible aspirational goal of recording every relevant empirical aspect of the organism's environment, sensation, neural activation, and behavior.
- Specifically, we will record full-body kinematics and binocular gaze data in order to directly simulate the **BINOCULAR RETINAL OPTIC FLOW** patterns associated with the animal's real-world environment interactions ((Matthis et al., 2018)).
- These patterns capture the geometric aspects of the Animal/Environment interaction, and provide estimates of the task-relevant environmental illumination patterns that the ocular and visual systems evolved to detect.
- These estimates will guide [THE WAY WE DO **NEUROPIXEL** STUFF] and [THE WAY WE DO THE END OF LIFE RETINA STUFF], with the goal of understanding the neural structures and functional pathways that define the animal/environment behavioral coupling.

Measurements:

Direct measurements

- **BODY:** Full 6 DoF kinematics all body segments (esp the skull) in world-centered coordinates
- **EYE:** Binocular horizontal, vertical, [torsional] position of each eye, in HEAD-CENTERED coordinates
- **ENVIRONMENT:** Create accurate 3d models and representations of the enclosure space where the activities take place
- **NEURAL** activity data (precisely time-synchronized to the BODY and GAZE data streams)

Derived Measurements

- From **BODY** data, we can compute:
  - **LIMB COHERENCE** - Measuring coherence between movement patterns of Left/Right/Fore/Hind limb pairs
  - **LOCOMOTION** - e.g. locomotor state, direction, speed, efficiency, etc

- With **BODY** + **EYE** data, we can compute:
  - **GAZE:** Binocular horizontal, vertical, [torsional] position of each eye in WORLD-CENTERED coordinates ((Matthis et al., 2018))
- With **GAZE+ENVIRONMENT**, we can compute:
  - **GAZE TARGET** (e.g. (Wallace et al., 2025))
    - Projecting binocular gaze vectors into the world to identify when **TARGET** falls onto Area Centralis
  - **RETINAL OPTIC FLOW** ((Matthis et al., 2022)):
    - Simple spherical pinhole camera model of the eye combined with gaze estimates gives us 6 DoF (technically 5 DoF because we don't have torsion) of each eyeball trajectory as the animal moves through its environment.
    - Projecting the **ENVIRONMENT** onto the back of the eyeball model and tracking changes over time provides an estimate of retinal motion associated with the real-world recorded behavior of the animals over the course of their development.

Apparatus

- This apparatus represents a 1m^2 behavioral arena outfitted with the following spatially calibrated and temporally synchronized empirical systems:
  - Full-body kinematic markerless motion capture (90Hz)
  - 6-axis head-mounted Inertial Measurement Unit (IMU)
  - Binocular eye/gaze tracking (200x200px, 200Hz in each eye)
  - Head-mounted (first person view) camera (400x400px, 120Hz)
  - Neuropixel recordings (??? Numbers, Hz, etc)

- We have the following mechanisms of environment manipulation:
  - Automatically controllable mouse target
    - Controlled via 2-axis magnetic gantry
    - Houses a tasty treat that the animal gets to eat if they catch the target
    - Can be automated or manually controlled
  - 360-degree virtual reality display
    - controllable via closed loop connection to the head sensor

Planned activities

Lifespan experiences

- Gather longitudinal recordings from ferrets across lifespan in either `Control` or `Manipulated` condition (specific manipulation TBD)

- Record every day from birth until XXX weeks

- At end of lifespan:

  - Chronic anesthetized measurements to get:
    - retinal sensitivities to light, motion, color, etc

  - Full histological assay to record:

    - **Musculoskeletal aspects**:
      - muscle volume/cross sectional area
      - bone density and functional morphology
      - bone/tendon junctions
      - etc

    - **Neural aspects:**
      - (??? Neurosceincey stuff of relevant cortical and subcortical areas)

    - **Ocular aspects**:
      - IOR of cornea
      - location/size of lens
      - Pupil size extents (at max/min iris constriction??)
      - Oculomotor muscle max/min length(??)

Control condition

- Place animals in **`Control`** condition
  - Raised in "optimal" lighting (nice and bright, full spectrum, day/night cycle)
  - Rewarding standard interactions with the target mouse (with a tasty treat and a happy BEEP on successful capture)
  - Normal/Veridical relationship between movement and virtual environment (1:1 optic flow in response to head movement)

Manipulated condition

- Animals in **`Manipulated`** condition (wherein we alter the developmental environment in some way),
  - Manipulations:
    - Perceptual Input:
      - Raised in the dark (or in a particular color of light)
      - Single eye suture (no binocular info)
    - Environment:
      - Slippery surface (place low-friction surface on ground of arena)
      - Manipulated/non-veridical relationship between movement and virtual environment (manipulate optic flow gain, direction, etc relative to animal movement)
    - Task:
      - Manipulated rewarding interactions with target mouse (always turns left, always retreats linearly, etc) - I think we should do this one!
      - Non-rewarding interactions with the mouse (same as Control, but no treat!!)

Bibliography

Fajen, B. R. (2003). A Dynamical Model of Visually-Guided Steering, Obstacle Avoidance, and Route Selection. *International Journal of Computer Vision*, *54*(1/2), 13–34. https://doi.org/10.1023/A:1023701300169

Hayhoe, M., & Ballard, D. (2005). Eye Movements in Natural Behavior. *Trends in Cognitive Sciences*, *9*(4), 188–194. https://doi.org/10.1016/j.tics.2005.02.009

Matthis, J. S., Muller, K. S., Bonnen, K. L., & Hayhoe, M. M. (2022). Retinal Optic Flow during Natural Locomotion. *PLOS Computational Biology*, *18*(2), e1009575. https://doi.org/10.1371/journal.pcbi.1009575

Matthis, J. S., Yates, J. L., & Hayhoe, M. M. (2018). Gaze and the Control of Foot Placement When Walking in Natural Terrain. *Current Biology*, *28*(8), 1224–1233. https://doi.org/10.1016/j.cub.2018.03.008

Wallace, D. J., Voit, K.-M., Martin Machado, D., Bahadorian, M., Sawinski, J., Greenberg, D. S., Stahr, P., Holmgren, C. D., Bassetto, G., Rosselli, F. B., Koseska, A., Fitzpatrick, D., & Kerr, J. N. (2025). Eye Saccades Align Optic Flow with Retinal Specializations during Object Pursuit in Freely Moving Ferrets. *Current Biology*, *35*(4), 761–775. https://doi.org/10.1016/j.cub.2024.12.032

Warren, W. H. (2006). The Dynamics of Perception and Action. *Psychological Review*, *113*(2), 358–389. https://doi.org/10.1037/0033-295X.113.2.358