

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

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

Benjamin Scholl¹ · Jonathan Samir Matthis^{2,3}

¹ University of Colorado Anschutz · 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 1m² 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:
 - (??? Neuroscience 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>