Probing behavioral compositionality in a reconfigurable 3D environment

Tzuhsuan Ma[1], **Ann M Hermundstad**[1], **and Jakob Voigts**[1]
{mat, hermundstada, voigtsj}@janelia.hhmi.org;
[1]HHMI Janelia Research Campus, Ashburn, VA 20147

Abstract

In natural settings, animals must navigate richly-structured sensory surroundings and rapidly adapt to changes in these surroundings. While many studies have explored navigation in mazes and open arenas, relatively little is known about how animals navigate in naturalistic terrain without clearly defined routes. Here, we probe the structure of mouse behavior in a complex, reconfigurable 3D arena in darkness and without explicit reinforcement. Mice quickly converge on a set of running and jumping paths through the arena. We developed new algorithms to partition this behavior into a set of motifs based on re-occurring path segments; this enabled us to describe long paths as hierarchical compositions of shorter sub-paths. Among the paths taken by the mice, highly compositional paths are lower in entropy, emerge later in time, and traverse more sensory diverse regions of the arena. We then introduced a local perturbation to the arena that interacted with existing composite paths. This led to a rapid emergence of new motifs that elicited non-local changes in behavior. Together, these results provide a lens for studying complex, long-timescale behavior by quantifying its compositional structure.

Keywords: navigation, complex behavior, decision-making

Results

Experimental setup and behavioral analysis. We filmed mice in a complex arena of 1.8 m diameter made from 153 hexagonal tiles of 17 cm diameter (Fig 1a) (Newman et al., 2023). Tile heights varied in steps of 2.5 cm to produce a variety of local shapes, from small steps to tall towers that could not be easily jumped. The arena was illuminated with infrared LEDs and otherwise dark, limiting sensory information to tactile and auditory cues about the local arena shape and olfactory cues left by the mice. Mice explored the arena in their dark period over four 8-hour sessions on consecutive days, and were housed in their home cage in between. We used an overhead camera and SLEAP (Pereira et al., 2022) to track the mice at ~ 25 Hz. Mice covered the majority of the arena after 25 min (Fig 1b). They quickly established preferred paths that they executed at a higher frequency compared to other equally-plausible paths (Fig 1c), including jumps across distances exceeding the range of their whiskers. This indicates that mice converge on and repeatedly generate a specific structured set of paths despite no explicit reinforcement.

Extracting composable motifs via a hierarchical segmentation algorithm. Were stereotyped paths learned as self-contained sequences, or were they composed of segments that mice had previously generated? To examine these possibilities, we performed a binary tree segmentation for extracting composable motifs that are repeatedly combined to construct different paths (Fig 2a-d). For a given portion of a path, the algorithm finds other instances of coinciding sub-paths within a half tile-width, and counts how many times these sub-paths happen in the past or future. These sub-paths are then tallied into a length-dependent *path occupancy map* (Fig 2c), normalized by how frequently each length occurs. We define a path to be highly compositional if it can be hierarchically segmented into sub-paths. This segmentation is similar to modularity-based clustering; i.e., a parent path is split into two sub-paths only when the summed occupancy of those sub-paths is greater than that of the parent path. We use the mean occupancy per split to define the *compositionality* of a path: $C = \frac{1}{1+n_{\text{splits}}} \sum_i \mathrm{occ}(\text{subpath } i)$. We consider high-occupancy sub-paths to be composable motifs.

Highly compositional paths correlate with diverse sensory experiences. To understand what differentiates compositional paths from other paths taken by the mice, we asked how the sensory experience of the mice might differ along these paths. We divided all paths of length 100 (25 tiles wide) into 3 groups based on their compositionality: low (bottom 1/4), medium (middle 1/2), and high (top 1/4) (Fig 3a). We found that highly compositional paths are more stereotyped, as summarized by a smaller *occupancy entropy* (Fig 3a). We used the sequence of local terrain shapes along a path (i.e., the relative heights of surrounding tiles) as a measure of an animal's egocentric *sensory experience* (Fig 3b). By computing the euclidean distance between any two sensory experiences, we found that the distribution of egocentric sensory differences was higher among highly compositional paths (Fig 3b), despite these paths being less diverse from an allocentric view. This result could provide normative insights about why mice prioritize certain path compositions over others.

Local perturbations reveal latent nonlocal motifs linked by compositional paths. To further probe how mice configure these compositional paths, we perturbed the arena on day 4 by swapping two tiles at a hub of many branching paths (Fig 4a). Although the perturbation was local, it had nonlocal consequences on the structure of behavior (Fig 4b-d), marked by a rapid emergence of local and nonlocal motifs that were linked by new compositional paths. This suggests that mice had learned a large reservoir of latent motifs without explicit behavioral repetition, and could configure these motifs into new paths in response to changes in the environment. Looking ahead, judiciously designed perturbation experiments could be used to probe this latent space of motifs.

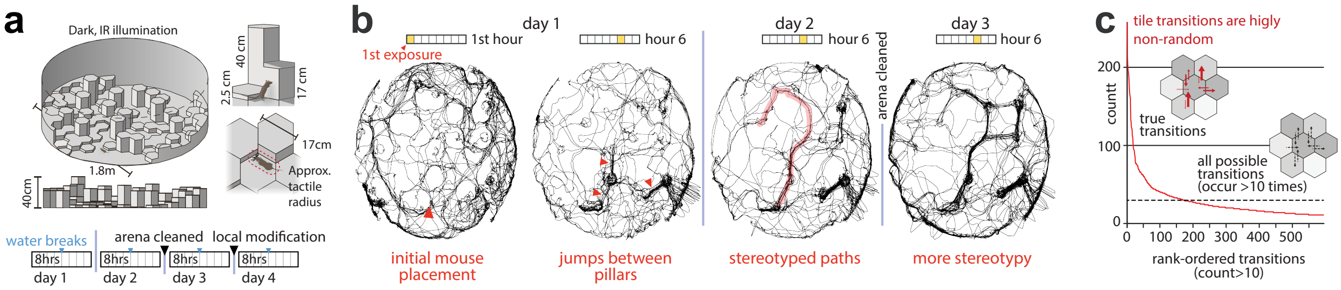

Figure 1: Mice generate richly-structured behavioral trajectories when exploring complex environments. a) Exerimental setup. **b)** Example paths from one-hour segments from one mouse. Paths become more sterotypical over time, and include long runs and jumps between high pillars. **c)** Histogram of rank-ordered tile transitions. A small subset of transitions occur with high frequency; the bulk of remaining transitions occurs infrequently.

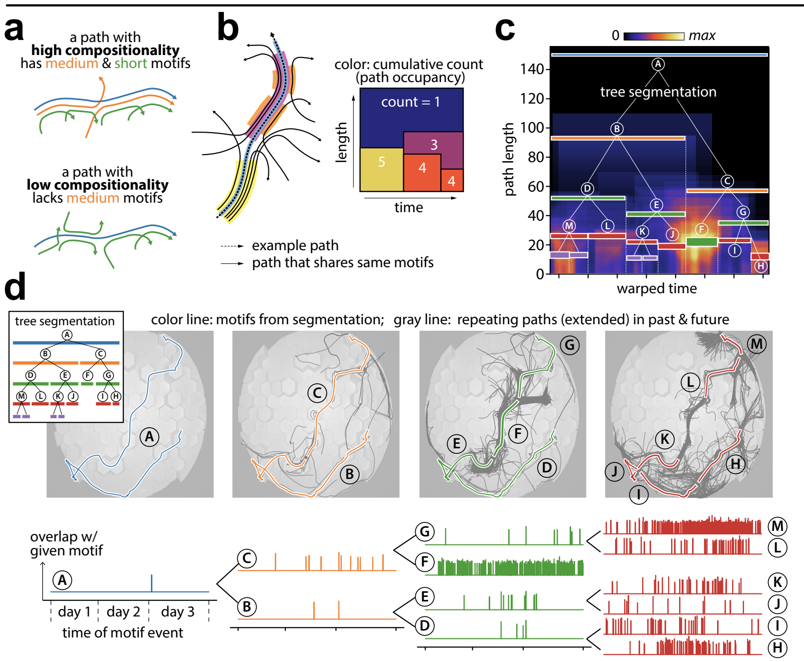

Figure 2: We segment paths into composable motifs. a-c) We design a tree segmentation to extract composable motifs by 1) constructing a path occupancy map that measures how often paths of varying lengths are repeated over time (b), and 2) using this map to iteratively segment a path into maximum-occupancy subpaths (c). Note that subpath F is not split—splitting does not further increase occupancy. **d)** Motifs are reused over time.

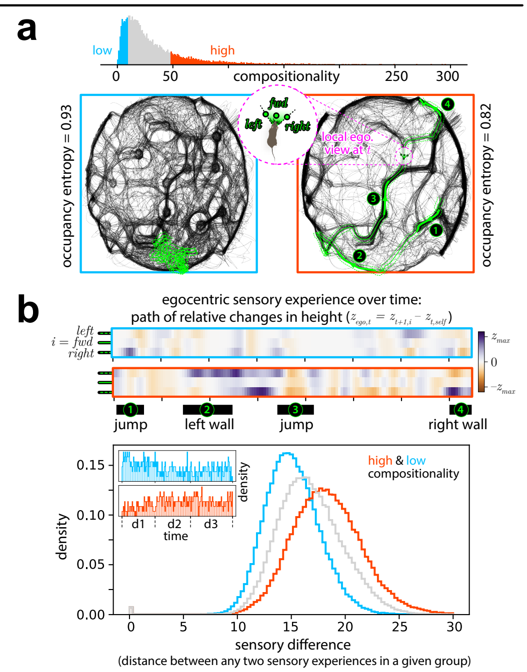

Figure 3: Highly compositional paths are more sensory diverse. Paths with high compositionality (red) have lower occupancy entropy (a) but traverse more sensory-diverse regions of the arena, measured by relative changes in height along a path (b).

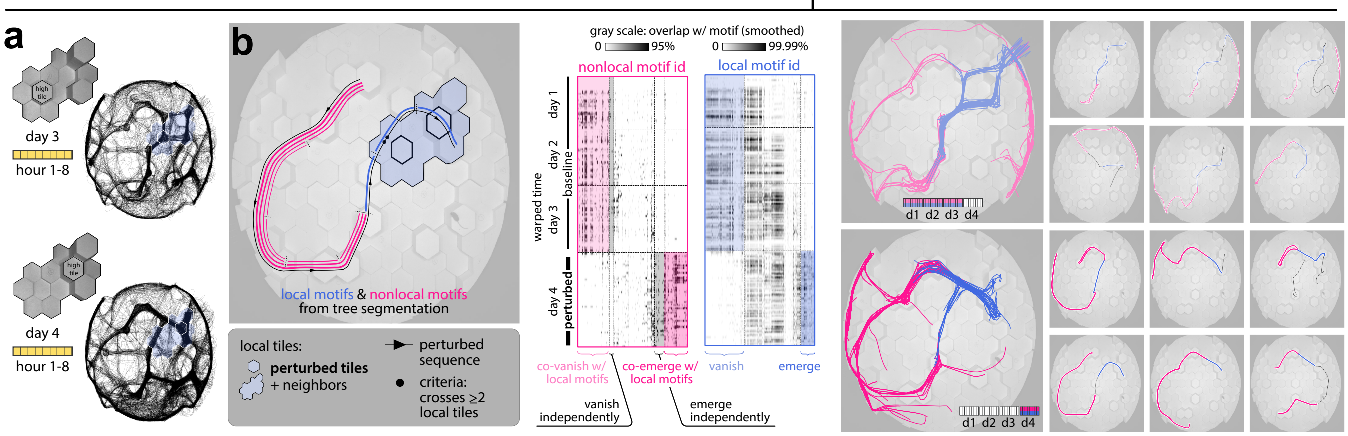

Figure 4: A local perturbation causes a global path reorganization. a) A perturbation is performed on day 4 by locally swapping two high tiles. **b)** Left panel: we segment a repeating path into local motifs that cross at least 2 local tiles, and nonlocal motifs that do not cross local tiles. Right panel: we track the occurrence of local and non-local motifs over time, and use this to identify motifs that emerge only after the perturbation. **c)** Left panel: local and nonlocal motifs that co-vanish on day 4. Right panels: individual example paths. **d)** Same as (c), shown for motifs that co-emerge on day 4.

Acknowledgments

This work is funded by the Howard Hughes Medical Institute. We thank Nishan Shettigar, Emily Dennis and Roian Egnor for helpful discussions, and Angela Jacobs for husbandry and experimental support.

References

Newman, J. P., Zhang, J., Cuevas-Lopez, A., Miller, N. J., Honda, T., van der Goes, M.-S. H., ... others (2023). A unified open-source platform for multimodal neural recording and perturbation during naturalistic behavior. *bioRxiv*.

Pereira, T. D., Tabris, N., Matsliah, A., Turner, D. M., Li, J., Ravindranath, S., ... others (2022). Sleap: A deep learning system for multi-animal pose tracking. *Nature methods*, *19*(4), 486–495.