Figures and figure supplements

Reconceiving the hippocampal map as a topological template

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Figure 1. Compressible U/zigzag track (Track A). (A) Top-down view of the four-meter long track with both arms in a semi-contracted configuration. (B) A schematic representation of the track illustrating how the segments are numbered in the planar (B) and the linear (C) frames of reference. (Note that the track depiction in C is drawn at half the scale as in B). The track was designed so that the angle between the segments 1 and 2 and between segments 3 and 4 on the top arm remain the same whether the track arm is extended or compressed, that is, $\angle(1,2) = \angle(3,4) = \alpha$. Similarly, the angles on the bottom arm remain equal, $\angle(7,8) = \angle(9,10) = \beta$. The magnitude of angle $\alpha$ is defined by the stretch of the top arm (by the position of the food well F$_1$), and angle $\beta$ is defined by the position of the food well F$_2$. Thus, the geometric configuration of the track can be described either by the angles ($\alpha$, $\beta$) or the positions of the food wells F$_1$ and F$_2$. (D) To more readily denote track arm configurations, we divided the space that can be occupied by the fully extended top and bottom arms into 12 vertical sections each. Each position of a track arm can be described by the numbered vertical section into which F$_1$ or F$_2$ (for the top and bottom arms, respectively) falls. In the depicted track configuration, F$_1$ falls into section 2 and F$_2$ falls into section 9. However, because we are interested in being able to denote changes in track segment positions in order to compute correlation coefficients, the top arm can be said to move from position $i$ to position $j$ (numbers in red), and the bottom arm from position $k$ to position $l$ (numbers in blue; see ‘Materials and methods’). So the track configuration depicted here can be fully described by F$_1 = 2$ and F$_2 = 9$. Given movement of an arm from section $i$ to $j$ (or $k$ to $l$), the larger the difference between the numbers, $d=|i − j|$ or $|k − l|$, the more geometrically dissimilar positions $i$ and $j$ or $k$ and $l$ are.

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Figure 1—figure supplement 1. Calculating correlation coefficients for place cells firing in different track configurations. The grid covering the 2D space occupied by the track is binned into squares that are 3 cm × 3 cm. The red line illustrates how we sequenced the bins in the planar and linear reference frames, with \( m = 1 \) at the top right square, \( m = 2 \) the square below it, etc. The activity vector \( u_i \) or \( u_j \) is the firing rate of a place cell given a particular track configuration (on the left, \( i \) on the right, respectively) in the 2D frame of reference and is constituted by the firing rates of the cell in particular bins (\( u_{i1}, u_{i2}, \ldots, u_{in} \)). In the example in panel A, the same spatial bin produces vector components \( u_{i,m} \) (in configuration \( i \)) and \( u_{j,m} \) (in track configuration \( j \)). We calculate the correlation coefficient, \( C_{ij} \), to understand the relationship between two activity vectors for a given place cell firing in two different track configurations (for the sake of simplicity, we depict only a change of position in the top arm, from \( i \) to \( j \); we can do this safely because the place cells we recorded did not have multiple place fields). Note that any given configuration can be arrived at from a number of movements: the top arm could move to position 2 from vertical sections 1 or 3, 7, or 10 (see Figure 1D), so the correlation coefficient for a cell that has a place field on the top arm, \( C_{ij} \), would be denoted by \( C_{1,2}, C_{3,2}, C_{7,2}, \) or \( C_{10,2} \), respectively. As explained in Figure 1D, the greater the numeric difference between \( i \) and \( j \), the greater the geometric difference between track configurations 1 and 2. The correlation matrix in the middle graphically depicts correlation coefficients by color. In panel B we show activity vectors \( v_i \), \( v_j \) for linearized trajectories of the animal along the same configurations \( i \) and \( j \) depicted in 2D in panel A.

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Figure 2. Place cell spiking across different configurations of Track A shows that place fields remain stable despite large geometric changes. Depicted are the firing patterns of two place cells: one cell that was active primarily on one dynamic segment of the track (A–D) and another place cell that was active on a static part of the track (E–H). (A) Each green dot represents a spike, which is shown in two reference frames: 2D (upper row) and linear (bottom row). The gray line represents the animal’s path across all trials with these configurations. (B) Overlaying the 2D and linear reference frames shows that the spiking is distributed in 2D space but much more localized in the linearized reference frame. (C) The matrix of the correlations between the activity of this place cell over the moving sections of the track defined in planar (left) and in the linear (right) frame. The color of each square \((C_{ij})\) represents the mean correlation coefficient between two track configurations, configuration \(1\) and configuration \(2\). The correlations were clearly much higher in the linear frame. (D) The mean correlation coefficient values, \(r_d = \langle C_{i,i+d} \rangle\), averaged over all pairs of the track configurations separated by \(d\) bins. The lines show whether the place cell firing was stable across configurations in the linear (1D, red) and the planar (2D, black) reference frames as a function of the difference \(d\) between the two configurations; the black line shows clear decay of correlation between the configurations, meaning that place cell firing was not stable in 2D (See Figure 1 for explanation of D). (E–H) The same plots for a different neuron (spikes shown in blue) that was active on the static track segments. The graph to the right shows a high correlation coefficient for both frames of reference, indicating that the place cell firing was highly stable in both frames.
fields were stable. The asterisk above the SEM error bars indicates $p < 0.001$. A total of 557 neurons were recorded; the place cells depicted here are representative.

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Figure 3. Place cell firing is stable across different track configurations. (A–C) The correlograms for the ensemble averages for each of three animals. The place cell spiking data are taken from only the segments of the track that change position between configurations. The two lines on the graphs in the third column represent the correlation.
coefficients of place cell ensembles in the 1D (red) and 2D (black) frames of reference. The correlation coefficients in the 1D configuration (red lines) remain stable, but the correlation coefficients for the 2D configuration (black lines) decay as the geometric difference between track configurations increases. (D) Combined data from all three rats for the correlation coefficients for the combined ensemble averages over all mobile track segments. Only data from the moving segments of the track and the corresponding correlations vs track configuration separation plot for the two reference frames are included. Firing across the population was much more stable in the linear reference frame. (E) The same plots as in D for spikes fired over the static sections of the track. Error bars represent SEM and * indicates p < 0.001.

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Figure 3. Continued

Figure 4. Protrusion-flip track (Track B). (A) Schematic representation of Track B, with segments numbered, showing the position of the track’s protrusion during two successive run sessions. (B–D) Each show a representative place cell firing in the two configurations. (E) Correlations for each of the four comparisons of regions across the two configurations. The rescaled correlation is highest, indicating that the data are most compatible with a scheme in which the place cell firing does not simply respond to changes in geometry. Error bars represent SEM with * and ** indicating p < 10⁻⁸ and < 10⁻⁹, respectively.

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