Hexadirectional coding of trajectories through an abstract multidimensional social network during decisions

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Abstract:

Recent findings suggest the hippocampal-entorhinal (HPC-ERC) system may serve a general mechanism for representing and navigating cognitive maps of spatial and non-spatial tasks. These map-like representations can be used to guide flexible goal-directed decisions. However, it is unclear whether this system, and the interconnected medial prefrontal cortex (mPFC), use the same principles to organize discrete entities along abstract dimensions during decision making in the absence of continuous sensory feedback. During training, participants learned the relationship between 16 entrepreneurs by comparing pairs of entrepreneurs at neighboring ranks in each of two ability dimensions. During fMRI, an entrepreneur was presented with two potential collaborators. Participants were asked to choose the better partner for a given entrepreneur. We found that the level of pattern dissimilarity in the HPC and ERC increased with the pairwise Euclidean distance between entrepreneurs in the 2-D social network, suggesting that separately learned dimensions are integrated into a 2-D cognitive map. Moreover, the ERC, vmPFC, intraparietal area, and posteromedial cortex all display hexadirectional signals for trajectories between entrepreneurs over the reconstructed social space. Our findings show that a grid-like code in the human brain is extended for decision making over an abstract and discrete social space, which may suggest a general mechanism for model-based decisions.

Keywords: Hexadirectional coding; Entorhinal cortex; Default mode network; Abstract and discrete dimensions

Grid cells in the medial entorhinal cortex (ERC) implement a hexagonally symmetric grid code during spatial navigation that can be used for self-location and vector navigation (Bush, Barry, Manson, & Burgess, 2015; Hafting, Fyhn, Molden, Moser, & Moser, 2005). Recent findings suggest that this six-fold symmetric signal might serve as a general code for representing the relationship between any *continuous* feature dimensions (Behrens et al., 2018; Bellmund, Gärdenfors, Moser, & Doeller, 2018) (e.g. sound frequency (Aronov, Nevers, & Tank, 2017), bird leg and neck length (Constantinescu, O'Reilly, & Behrens, 2016), and odor intensity (Bao et al., 2019)). However, it remains unknown whether the human ERC uses the same principles to guide decisions over a task space that is characterized by abstract and discrete dimensions, in the absence of continuous sensory feedback.

To test whether the brain employs a hexagonally symmetric code to navigate a multidimensional social network during decision-making, we designed a novel task that required participants (n=21) to choose a better collaborator for a given individual by recollecting their relative ranks in two ability dimensions. During behavioral training, participants learned the relative ranks between individuals in two independent dimensions (competence and popularity) through feedback-based binary comparisons between individuals who differed by only one rank on one of two dimensions. Crucially, participants were never shown the 1- or 2-D structures but could construct them through transitive inferences. During fMRI, participants were shown face stimuli sequentially and asked to choose a better partner for an individual (F0) between two potential partners (F1 and F2) during F2 presentation (Fig. 1A). In our task the better collaboration is determined by the growth potential (GP) each pair can expect. To compute the GP, participants should weight the ranks of the group in both dimensions equally, with the rank of a group in each dimension determined by the higher rank individual between two entrepreneurs. Therefore, the GP corresponds to the area drawn by the relative rank of two entrepreneurs in the 2-D cognitive space (Fig. 1B). To compute the GP accurately, participants may recollect the relative positions of individuals in the mentally reconstructed social hierarchy.

We investigated two principal questions: 1) does the HPC-ERC system represent the position of individuals in the hierarchy as a cognitive map?; and 2) do the ERC and interconnected regions show a six-fold symmetric signal, as predicted from the ERC grid code, to represent trajectories through the abstract and discrete
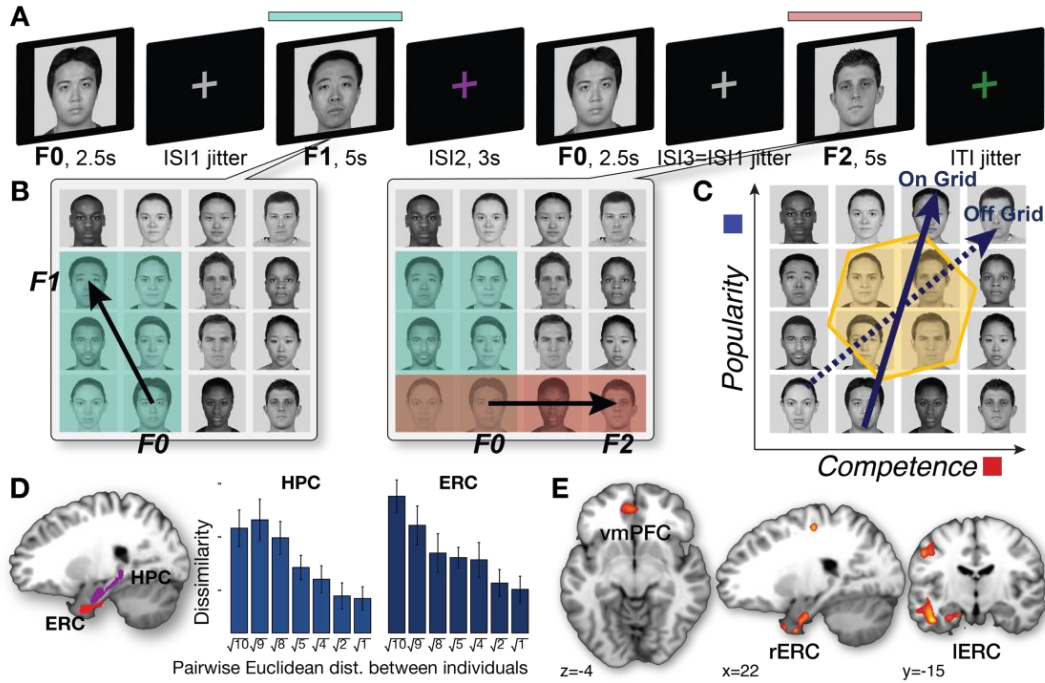
Figure 1

social space during binary decisions even when no sensory feedback is given (Fig. 1C)?

We first tested whether the brain represents the relative ranks between individuals in a 2-D Euclidean space characterized by two social dimensions (Nili et al., 2014). We found that the levels of pattern dissimilarity across voxels in a priori anatomically defined regions of interests (ROIs) in the HPC and ERC are explained by the pairwise Euclidian distance between individuals in social space (Fig. 1D), supporting hypothesis that the brain integrates separately learned representational structures into a 2-D cognitive map.

Next, we searched for neural evidence for hexadirectional modulation of the putative trajectories that theoretically guided participants to compute the growth potential in decision-making: $\overrightarrow{F0F1}$ at the time of F1 presentation; $\overrightarrow{F0F2}$ at the time of F2 presentation (see Fig. 1B). To first identify hexagonally symmetric signals across the whole brain, we tested for any areas where BOLD signal was modulated by any linear combination of $\sin(6\theta)$ and $\cos(6\theta)$ using a Z-transformed F-statistic, where θ is the trajectory angle between two individuals in social space. We found a significant effect of hexagonal modulation in the ERC (Z>2.3 and p<0.05). This effect has also shown in the medial prefrontal cortex (mPFC), intraparietal area, and posteromedial cortex (p<0.05 TFCE corrected) (Fig. 2A).
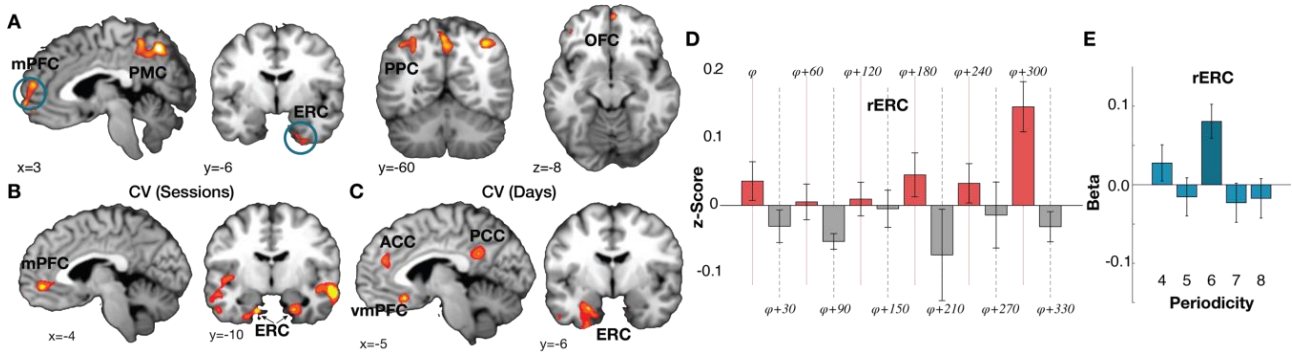

Figure 2

We further tested the consistency of the hexagonal symmetry in ERC in an unbiased way. Specifically, we separated the training dataset for estimating the putative grid angle (ϕ) from ERC from the testing dataset on which the effects of hexagonal symmetry were tested with the regressor, $cos(6[\theta_t - \phi])$. Moreover, this cross-validation (CV) procedure was performed not only across sessions acquired from the same day (Fig. 2B and D) but also across sessions acquired more than a week apart (Fig. 2C). We found a hexagonal modulation in a similar network of brain regions including the ERC and mPFC. We confirmed that this effect was specific for six-fold, but not any other control periodicities between four-, five-, seven-, or eightfold in ERC (Fig. 2E).

Finally, we found that the easier the decision ($|GP_{F0F1} - GP_{F0F2}|$), the greater the vmPFC and bilateral ERC activity. This finding supports the role of ERC and vmPFC in decision-making when it requires accessing a cognitive map to compare multidimensional values (Fig. 1E).

Collectively, our findings suggest that even abstract and discrete relational structures, never seen but inferred from the outcomes of binary decisions, are represented as a cognitive space such that each entity is located according to its feature values along relevant dimensions. Furthermore, we suggest that a grid-like code may underpin discrete decisions when they require accessing the cognitive map, even in the absence of continuous sensory feedback.

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