Grid cell meeting

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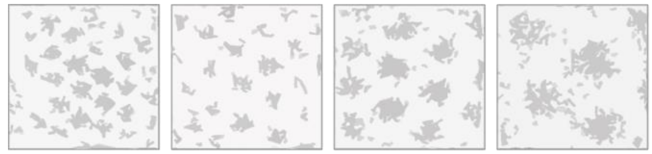

Poster presentations

1. Sanjeevan Ahilan, Gatsby Computational Neuroscience Unit, UCL

   Natural environments are replete with statistical structure and regularities over many spatial and temporal scales. Humans and other animals are adept at extracting this structure by building cognitive maps or world models, which support predictions of future states and requirements. However, such structure is often difficult to learn and use because it is obscure, involving long-range temporal dependencies. Here, we analysed behavioural data from an extended experiment with rats, showing that the subjects learned the underlying statistical structure, albeit suffering at times from immediate inferential imperfections as to their current state within it. We accounted for their behaviour using a Hidden Markov Model, in which recent observations are integrated with the recollections of an imperfect memory. We found that over the course of training, subjects came to track their progress through the task more accurately, a change that our model largely attributed to decreased forgetting. This `learning to remember' decreased reliance on recent observations, which may be misleading, in favour of a longer-term memory.

2. Nikolai Axmacher, Ruhr University Bochum

   Grid cells in rodents have been suggested to support path integration, and novel results indicate that rodents with impaired grid cell-like representations indeed show deficits in path integration performance. In humans, grid cell-like representations can be assessed via functional MRI. Several studies have shown that these grid cell-like representations are indeed functionally relevant, as they correlate with performance in spatial navigation tasks. However, their role for path integration performance is still unknown. We implemented a novel path integration paradigm that will allow us to dissect different navigational strategies and map them onto specific brain circuits including the entorhinal cortex. On the poster, I will present this paradigm and some pilot results.

3. Jacob Bellmund, Kavli Institute for Systems Neuroscience, NTNU

   The spatially periodic firing of grid cells is thought to provide a metric of space and has recently been implicated in mapping continuous dimensions of experience for cognitive functions beyond navigation. However, in freely moving rodents, environmental geometry strongly influences grid-cell firing. Specifically, firing patterns have been shown to be distorted in highly polarized environments such as a trapezoidal enclosure compared to less polarized environments such as a square. In humans, the spatial coherence of a hexadirectional fMRI grid proxy measure has been linked to spatial memory. Here, we address the question whether human spatial memory is influenced by environmental geometry in highly polarized environments using immersive virtual reality. Participants navigated a trapezoidal and a square arena to iteratively learn object positions. Spatial memory was assessed both within and outsid how the entorhinal grid system maps cognitive spaces for navigation and beyond.

4. Anne Bierbrauer, Ruhr-University Bochum

Grid-cell-like signals can be detected in human fMRI using a virtual spatial learning paradigm (Doeller et al., 2010; Kunz et al., 2015). In this paradigm, subjects learn the spatial locations of different objects during navigation in a virtual arena. The same paradigm has the potential to inform us about learning-related changes in spatial representations. We applied it in a human EEG study in order to find out how these representations are influenced by the current brain-state of the subject – in particular, by EEG oscillations that reflect neural excitability. We found that trial-by-trial differences in alpha-power relate to learning and thereby to the formation of spatial representations. In a consecutive simultaneous EEG-fMRI-study, we are planning to study the interrelation of the formation of spatial representations, the current brain state and grid-cell-like signals during spatial navigation.

5. Charlotte Boccara, King's College London

GOAL REMAPPING IN GRID CELLS

Originally thought as a universal invariant metrics for navigation, the rigid structure of grid cells was recently shown to be influenced by geometrical features. Yet it is not clear whether these changes are the result of a distorted perception of space, or whether they carry further behavioural role. Here, we trained rats to daily learn three new reward locations on the cheeseboard maze, while simultaneously recording from the medial entorhinal cortex and the CA1 region of the hippocampus. We showed that some grid fields are locally distorted toward goal location, leading to the degradation of the regular grid pattern. Thus, grid cells, like CA1 place cells, may contribute to goal representation during learning. This demonstrates that the grid code goes beyond simple metrics.

6. Jacopo Bono, Imperial College London

Recent theoretical and experimental work suggests that hippocampal place cells encode more than spatial information. Stachenfeld et al. propose that the firing rates of place cells represent a predictive representation of the animal's future states [1]. This framework qualitatively agrees with experimentally observed place field shapes and their evolution over time. While the authors used a normative approach inspired by reinforcement learning, we propose a biologically plausible implementation in a network of spiking neurons. We derive spike-timing plasticity rules that can reproduce this predictive map in hippocampal CA1 neurons. We then validate our models against experimental data from behaving mice. From this analysis, we can find restrictions on our parameter space and provide experimental predictions.[1] The hippocampus as a predictive map. Stachenfeld, Botvinick, Gershman. Nature Neuroscience 2017.

7. Sara Zannone, Imperial College London

Neuromodulation plays a fundamental role in the acquisition of new behaviours. It is still unclear, however, how neuromodulated learning is attained at the level of the network. We investigate this by combining experimental data from the hippocampus and a computational model of navigation.Our experimental data on mouse hippocampal slices show that acetylcholine biases spike-timing dependent plasticity (STDP) towards depression (Brzosko et al., eLife, 2017), while the subsequent application of dopamine retroactively converts synaptic depression into potentiation, effectively acting as an eligibility trace (Brzosko et al., eLife, 2015; Brzosko et al., eLife, 2017).We incorporate this sequentially-modulated plasticity rule (sn-Plast) in a spiking network model of a reward-based navigation task. We show that, thanks to dopamine-modulated STDP, our modelled agent can learn associations between actions and distal rewards, and can successfully navigate to the reward location. The addition of cholinergic depression, instead, enables learning from negative outcomes. This influences the exploration of the environment in a non-trivial manner that depends on the specifics of the model, the maze and the task. Furthermore, cholinergic depression also allows for flexible learning and relearning, especially useful in a real-world, changing environment (Brzosko et al., eLife, 2017; Zannone et al., arXiv, 2017).

8. Iva Brunec, University of Toronto

Spatiotemporal scaling along the hippocampal longitudinal axisThe properties of neurons in the hippocampus, a structure crucial for navigation, vary along its longitudinal axis. Place cells in rodent ventral hippocampus code for larger regions of space than those in dorsal hippocampus. A key question is whether evidence analogous to the cellular mechanisms identified in rodents can be observed with fMRI in humans. Using fMRI, we provide novel evidence for a gradient of spatiotemporal representations along the anteroposterior axis of the human hippocampus during large-scale spatial navigation. Consistent with rodent studies, we showed that the variability in voxelwise activity across space and time was greater in posterior hippocampus than anterior hippocampus (pHPC, aHPC), the human homologues of ventral and dorsal hippocampus in rodents, respectively. Importantly, greater variability in signal, particularly in pHPC, was linked to stronger reliance on map-based navigational strategies. In a follow-up study, we also found differences in goal coding properties along the longitudinal axis. These findings help account for converging evidence that the hippocampus supports a gradient of spatiotemporal representations along its longitudinal axis, where aHPC and pHPC code for coarse and fine-grained representations, respectively, enabling efficient navigation and flexible behaviour.

9. Daniel Bush, UCL Institute of Cognitive Neuroscience

Phase coding offers numerous theoretical advantages over an equivalent firing rate code. Empirical studies have provided evidence for phase coding across multiple species and cortical regions. The best known example comes from grid cells in rodent medial entorhinal cortex, which are characterised by a regular triangular array of spatial firing fields and exhibit phase precession – spiking at progressively earlier phases of the 5-11Hz theta oscillation as each firing field is traversed. It has often been assumed that such phase coding relies on a high amplitude baseline oscillation with relatively constant frequency. However, recent data demonstrate that grid cells in both bats and humans exist in the absence of a constant frequency oscillation in either the spike train or LFP. Here, we simulate a population of grid cells that phase precess against a baseline oscillation with highly variable frequency recorded from depth electrodes in human hippocampus. We show that this allows grid cell firing patterns to efficiently multiplex information about location, running speed, movement direction and a fourth variable such as anxiety. Finally, we describe analytical methods that can identify phase coding in the absence of a constant frequency oscillation, as in single unit recordings from the bat or human brain.

10. James Butler, UCL

Since the discovery of place cells and the 'cognitive map' by O'Keefe & Dostrovsky in 1971 much research has revealed the mechanisms underlying navigation of spatial environments. How mammals navigate abstract conceptual spaces, such as those that underlie complex cognitive processes, remains unclear. We therefore taught two rhesus macaques (Macaca mulatta) several abstract discrete environments composed of networks of associated stimuli (e.g. a 5x5 grid with 4 edges per node) using a novel behavioural paradigm. After just seven days of training subjects could successfully navigate to rewarded target locations several stimuli away with high precision. When learning a new environment, due to the high number of unique pathways (> 500), some routes would be encountered for the first time near the beginning of training whereas others would be encountered later in training. Subjects performed better in their first encounter of a unique pathway if it occurred later in training rather than earlier, demonstrating a global representation of the map. We have therefore shown that non-human primates can navigate complex abstract environments, extracting statistical knowledge in the process to facilitate their navigation.

11. Giulio Casali, UCL

In the horizontal plane, grid-cell firing fields are symmetric and regularly spaced, reflecting locomotion-related distance-measuring (odometry). We find that if the body plane is vertical, on a wall, then firing fields become expanded and irregularly distributed, hippocampal place fields become sparser, and several physiological indices of running speed show reduced gain. Thus, neural odometry operates in the body plane but is modulated by gravity, differentiating vertical from horizontal spatial perception.

12. Alexandra Constantinescu, UCL

Characterizing grid-like activity patterns in humans using 7T fMRI
Alexandra Constantinescu, Joseph Nour, Junjing Wang, Stuart Clare, Neil Burgess*, Tim Behrens*
When people think about 2D spaces, fMRI activity patterns corresponding to grid, place and head-direction cells can be seen, but characterizing these patterns, e.g. measuring gradients in grid-cell scale, is challenging. However, inhomogeneities in grid orientation and phase across grid cell populations could be leveraged to detect gradients in grid scales at the population level. We developed a novel 2D spatial autocorrelation analysis at the population level, using a representational similarity analysis approach. Using simulated data, we found that our method can detect hexagonal symmetry as a function of location in 2D space, across different grid scales. This pattern was specific to populations of grid cells, but not control noisy data. We next asked if such fine biases in the preferred grid phase across the population of grid cells could also be captured between different MRI voxels while people navigate virtual environments in a 7T scanner. We trained human participants to learn a spatial environment with high precision, and scanned their brains with sub-millimeter fMRI. We are currently analyzing these datasets with our method, and have been able to begin to characterize place-like codes in the human hippocampus.

13. Tiziano D'Albis, Humboldt Universitaet zu Berlin

Title: Recurrent amplification in a grid-cell network
Authors: Tiziano D'Albis and Richard Kempter
Grid cells are neurons of the medial entorhinal cortex that are tuned to the animal's position in the environment and whose firing fields form an hexagonal pattern in space [1]. Since their discovery, grid cells have been studied extensively, for their strikingly periodic tuning, and because they are believed to support high-level cognitive functions, such as self-location, memory, and navigation [2,3]. Nevertheless, to date, it remains unclear how grid-cell activity is formed and how grid cells interact within the cortical network.Grid cells are organized in discrete functional modules

characterized by similar scales and orientations and distributed spatial phases [4]. Because cells of the same module tend to respond in concert to external manipulations of the environment [4,5] and their spiking activity is temporally correlated [6], grid cells are thought to be recurrently connected. Yet the functional role of such recurrent connections is still debated. On the one hand, attractor models use structured recurrent connectivity to generate grid fields [7], but it is unclear how such a connectivity could emerge without an anchor to the physical space. On the other hand, feed-forward models can generate grids from spatially-selective inputs [8,9], but they largely neglect the recurrent dynamics within modules.Here we propose that broadly-tuned grid patterns could first be learned via spatially-irregular feed-forward inputs and then sharpened or amplified by the recurrent connections. To evaluate this hypothesis, we propose a minimal mathematical model of the neural activity within a grid-cell module. Using both analytical and numerical means, we study the conditions in which grid patterns could be recurrently amplified, and we quantify the amount of amplification as a function of the connection strengths and the quality of the input tuning. Finally, we show how a connectivity structure suitable for the amplification could spontaneously emerge from the activity correlations already present at the feed-forward input.
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14. Dora Csordas, Computational Neuroscience Department Biology II Ludwig-Maximilians-Universität Munich, Germany

Inbound and Outbound Spikes in Grid Fields

Csordas, Nagele, Stemmler, Herz

When a rodent moves, grid cells in its medial entorhinal cortex fire at the vertices of a hexagonal lattice spanning the environment [Hafting et al. 2005]. Based on the spike number on trajectory segments pointing towards or away from the firing field centers, De Almeida et al. [2012] argued that grid cells have prospective and retrospective modes. This motivated us to analyze the inbound and outbound spikes using the dataset from Latuske et al. [2015]. We found that there are more inbound than outbound spikes. At first sight, this suggests that grid cells mostly code prospectively, similar to findings from place cells [Mueller & Kubie 1989; Sharp 1999]. There is, however, also an alternative interpretation as the body position inferred from the tracking system may not coincide with the perceived self-center of the animal. Assuming that the "true" firing fields are ideally suited to guide the animal, we shifted spikes either in space or in time such that field size, spatial information or spatial coherence were optimized. When we then analyzed the spikes, their angular distribution was almost equalized when spatial shifts were applied, but not for temporal shifts.

15. Gily Ginosar, Weizmann Institute of Science

Grid cells recorded from animals exploring 2D planes, fire in an hexagonal pattern across the environment. However, many animals navigate through 3D space, but no studies have characterized the 3D volumetric firing of grid cells. Here, we trained Egyptian fruit bats (Rousettus aegyptiacus) to fly in a large room, while we wirelessly recorded single-neuron activity in medial entorhinal cortex (MEC). Our results revealed structured firing in the 3D firing-rate maps, with multiple firing-fields. The spacing between firing-fields was more variable than in perfect synthetic 3D lattices, but was less variable than shuffled data. Thus, some neurons exhibited a fixed distance scale, without forming a global lattice – supporting a distance-coding function for grid cells. We also found a number of other spatial cell types in the MEC, including (i) 3D border cells, (ii) 3D head-direction cells, and (iii) a new subset of MEC neurons that fired near landing-balls – oftentimes only at very specific balls. Taken together, these data suggest a rich 3D spatial representation in the MEC of flying bats – including coding of 3D space by grid cells, coding of 3D geometry by border cells, as well as object-related coding in the bat MEC.

16. R. Irene Jacobsen, NTNU

How is a place field generated? Developing a method for the functional identification of inputs to a single hippocampal neuronR Irene Jacobsen, Flavio Donato, Rajeevkumar R Nair, Clifford Kentros, May-Britt Moser, Edvard I MoserWe are developing a method that utilises a developmental approach to achieve extreme virus dilutions, which allows us to use a G-protein deleted rabies virus expressing Channelrhodopsin-2 (ChR2) to detect the monosynaptic inputs to a single cell in CA3. Using electrophysiology and light-mediated activation of ChR2 we can thus identify the spatial properties of input cells in layer 2 of the medial entorhinal cortex while the animal is exploring an open field environment.By targeting a large group of hippocampal cells with this method, we have been able to identify cells in the MEC that provide direct, monosynaptic input to the hippocampus, including grid and aperiodic spatial cells. We are also able to target a single cell in CA3, and are currently refining the protocol in order to functionally identify its inputs. Achieving this will not only allow us to define the inputs involved in the generation of place fields, but also further our understanding of neuronal integration at the level of single cells.

17. Misun Kim, UCL

Recent studies suggest that grid cells are an efficient neural mechanism for encoding knowledge about spatial location and also abstract cognitive information. The world, be it physical or abstract, is high-dimensional. However, grid cells have been mainly studied on a two-dimensional plane and little is known about how grid cells encode three-dimensional (3D) space. Here, we consider how to study 3D grid cells in humans using a novel 3D virtual reality paradigm and fMRI analysis method. This analysis relies on the known property of grid cells where their activity is modulated by the movement direction of animals relative to the grid axis. We found that signals in left entorhinal cortex were best explained by one particular 3D grid cell model - a face-centred cubic lattice model. This is the first empirical evidence for 3D grid cells in the brain. In conducting this study, we also developed interactive software to help researchers visualize 3D grid cells and predict the activity of these cells for varying movement directions and grid axis orientations. Our findings and software serve as an initial stepping-stone for studying grid cells in realistic 3D worlds and also potentially for interrogating abstract high-dimensional cognitive processes.

18. Lukas Kunz, Department of Epileptology, University Hospital Freiburg, University of Freiburg
Grid cells in rodents have been suggested to support path integration, and novel results indicate that rodents with impaired grid cell-like representations indeed show deficits in path integration performance. In humans, grid cell-like representations can be assessed via functional MRI. Several studies have shown that these grid cell-like representations are indeed functionally relevant, as they correlate with performance in spatial navigation tasks. However, their role for path integration performance is still unknown. We implemented a novel path integration paradigm that will allow us to dissect different navigational strategies and map them onto specific brain circuits including the entorhinal cortex. On the poster, Nikolai Axmacher and I will present this paradigm and some pilot results.

19. Marcus Lewis, Numenta
Title: Using grid cells for coordinate transforms.
The cortex and hippocampus have multiple cell populations that track locations. Many of these represent different reference frames, but it's not clear how these populations interact and work together. In this work, we show how grid cells can compute flexible coordinate transformations between two maps. Suppose a pair of grid cell populations track two locations: the animal's location in the environment, and its location relative to a source of food. A third cell population could detect the spatial relationship -- the "transform" -- between these two maps. Recalling this transform, the animal could detect its location relative to food by recognizing its location in the environment. This "transform" represents a 1-to-1 mapping between the firing fields of individual grid cells of the two populations. These mappings exist for all translations and for many rotations, so grid cells can perform any translational transform and many transforms in which the maps are rotated. Each grid cell "module" can compute this transform locally, independent of other modules, so the circuit can transform novel multi-module representations. The brain may use this grid cell transform to represent the spatial relationship between environments and goals, between scenes and objects, and between objects and features.

20. .Yunzhe Liu, UCL
Flexible behaviour is thought to be underpinned by neural models of the world that account for the relationships between experiences. In rodent spatial navigation, hippocampal and neocortical replay and preplay are considered important for building such models. In replay, patterns of cellular firing during rest spontaneously play out past spatial trajectories in both forward and reverse directions, and reverse replays are increased for rewarded trajectories. This computation is also implied by Dyna-type learning algorithms. In preplay, future trajectories are played out, perhaps constrained by structural knowledge of possible relationships in the world. However, despite the theoretical importance of neural replay, its study has so far been largely restricted to spatial navigation tasks in rodents. Furthermore, it is unclear whether knowledge of task structure can indeed impact on thesequences that are played during rest. Using magnetoencephalography (MEG), our goal here was to test 1) is there non-spatial replay during rest in humans, and 2) can replay generalise learnt structure to new stimuli? We exploited a revised sensory preconditioning paradigm to build two distinct sequences: participants were presented

with pairwise associations where the correct sequence is jumbled in time, and pre-trained to re-assemble them in the right order. By building pattern classifiers for MEG sensor activity for each stimulus, we could detect sequences of their reactivations during rest. These reactivations recapitulated known features of hippocampal replay but in a non-spatial task. Transitions were rapid (40-70ms lag) and forward replay transitioned to reverse replay after new learning (including after reward). Notably, the replayed sequences reflected the correctly re-assembled sequence, not the viewed sequences, implying that task structural knowledge can impose constraints on replay. Our data extend known spatial replay mechanisms to human reinforcement learning and suggest such replay can reflect new sequences beneficial for future behaviour rather than simply recapitulating past events.

21. Shachar Maidenbaum, Columbia University NY

Grid cells are a fundamental part of the brain's spatial system, playing an important role in tasks such as path integration and spatial memory. In rodents grid cell activity is thought to rely on large-scale theta oscillations in the entorhinal cortex. However while theta oscillations were detected in the human entorhinal cortex, they are harder to see and more variable. To examine the role of network oscillations and grid cells in humans, we test the hypothesis that in the human entorhinal cortex theta power exhibits a population-level signature of grid cells—hexadirectional-modulation by heading. We collected intracranial electroencephagraphic (iEEG) data from patients performing a virtual spatial memory task, and found hexadirectional-modulation of high-theta band (5-8Hz) power during navigation. This pattern matched predictions from rodent and fMRI literatures—specificity to the theta band, to 6-fold symmetry and to the entorhinal cortex. Grid orientation was stable in each subject, but differed between subjects. Furthermore, hexadirectional-modulation level correlated with behavior—stronger modulation predicted better spatial memory task performance. These results are important theoretically by demonstrating a link between theta oscillations and the grid system in humans and practically by showing that detailed neural processing features can be identified from population-level neural recordings, extending noninvasive imaging findings.

22. Rob Mok, UCL Experimental Psychology

A clustering model for concept learning that produces place and grid cell-like activity: the non-spatial cognitive mapRecent work suggests that place and grid cells play a role in mapping abstract relations in conceptual spaces. This bears a striking similarity to ideas in category learning, where objects lie in a multidimensional feature space and cluster around their category. We propose that the brain might use a general algorithm to represent features in conceptual tasks and space during navigation. We present a clustering model that successfully models concept learning data and produces place and grid cell-like activity during navigation. In the category-learning task, objects were sampled from a continuous two-dimensional feature space and belonged to one of two categories. The model starts with 'clusters' at random points in the space and attempts to find category centres. After training, clusters converged around the mean location of the members in each category. In the ‘navigation’ context, locations were uniformly distributed across two-dimensional space. After training, the clusters spread out and formed a hexagonal grid. We propose that place (or concept) cells are clusters in feature space, and grid cells represent the entropy, or uncertainty, over cluster assignment, like in category learning models.

23. Timothy Muller & James Whittington, University of Oxford

A central problem to understanding intelligence is the concept of generalisation. This allows previously learnt structure to be exploited to solve tasks in novel situations differing in their particularities. Here we propose that in order to generalise knowledge, the representations of the structure of the world, i.e. how entities in the world relate to each other, need to be separated from the representations of the entities themselves. We propose a novel model where structural information provided by higher order cortex (grid cells) and sensory information provided by sensory cortex is combined to form a conjunctive representation in hippocampus (place cells). The model is trained end-to-end in an artificial neural network that resembles a variational autoencoder, where the task is to predict the next vertex on multiple graphs that share the same structure but with shuffled vertices. For graphs with 2D structure, grid and place cell representations naturally emerge, without any training for navigation. Using data of simultaneously recorded grid and place cells in a remapping experiment, we test the prediction that grid cells impose a structural constraint on place cells and thus grid-place relationships are preserved across environments.

24. Matthias Nau, Kavli Institute for Systems Neuroscience / NTNU

Entorhinal grid cells map the local environment but their involvement beyond spatial navigation remains elusive. We examined human fMRI responses during a highly controlled visual tracking task and show that entorhinal cortex exhibited a six-fold rotationally symmetric signal encoding gaze direction. Our results provide evidence for a grid-like entorhinal code for visual space and suggest a more general role of the entorhinal grid system in coding information along continuous dimensions.

25. Tobias Navarro Schroeder, Kavli Institute For Systems Neuroscience, NTNU

Grid cells are the hallmark of the brain's coding system for space. They are situated in the superficial layers of the medial entorhinal cortex. One of the areas first affected in Alzheimer's Disease. Understanding the neuronal mechanisms that give rise to them, and how to measure their activity with non-invasive methods has therefore high clinical relevance. Hexadirectional modulations of the fMRI signal during virtual navigation have been previously described, and likely reflect population activity of grid cells. However, it remains unknown how their activity is linked the the hemodynamic fMRI activity. Here, we employed a human VR navigation experiment using magnetoencephalography (MEG) and find hexadirectional signal modulations in a high-frequency band (60 Hz-120 Hz). Next, we leveraged analyses of grid cell activity in conjunction with local field potential (LFP) recordings in rats. We found hexadirectional LFP modulations in freely navigating rats in the same frequency band as in the human MEG study, and the preferred orientation of this hexadirectional modulation anchored to the axes of the grid cell firing rate maps. These findings describe new ways to measure grid cell proxy measures with MEG. Crucially, we directly link grid cell activity to measures of population activity in rats and humans. Thereby, we shed new light on the physiological basis of non-invasive grid cell proxy measures.

26. Jake Ormond, Sainsbury Wellcome Centre

Study of the hippocampal place cell system has greatly enhanced our understanding of memory encoding for distinct places, but how episodic memories for distinct experiences occurring within familiar environments are encoded is not clear. Using an aversive spatial decision making task which induced partial remapping in CA1, we examined whether episodic experiences engaged a unique population of hippocampal neurons. We found that remapping cells exhibited distinct features not present in non-remapping cells. During memory encoding, they showed shifted theta phase preferences, suppression by aversive stimuli and their remapping closely tracked behavioral learning. Following learning, remapping cells were more heavily involved in awake replay events, their degree of involvement correlated with their subsequent post-learning stabilization and they developed correlated firing patterns in aversive regions of the environment. Our data demonstrate a sequence of events occurring within a plastic subpopulation of CA1 place cells leading to the rapid incorporation of behaviorally relevant contextual information into a stable spatial representation.

27. EunHye Park, New York University

The spatial discharge of many medial entorhinal cortex (MEC) and hippocampus cells can be classified into functional classes that are hypothesized to collectively constitute a cognitive map, the unitary neural representation of space used for navigation. We evaluated whether MEC and hippocampus CA1 representations of space are coherent during navigation that requires two distinct representations of the environment. Rat MEC and CA1 principal cells were recorded during active place avoidance navigation across three task phases: stable1 (S1)-rotating (R)-stable2 (S2). Basic features like the firing rates of all cells were unchanged across the phases. Despite excellent navigation, spatial tuning of MEC head-direction and grid cells, and CA1 place cells degraded during rotation and partially reverted when rotation stopped for S2. We measured sub-second (e.g. 40 ms) temporal correlations in the discharge of cell pairs during each recording and used the correspondence between two recordings to estimate representational invariance across the conditions. Correlations within MEC ensembles were unchanged by rotation indicating representational invariance, CA1 cell pair discharge correlations were less well maintained than MEC cells across two recordings (S1xS2 $r=0.39$; S1xR $r=0.31$) as were the correlations between MEC head-direction cell - CA1 place cell pairs (S1xS2: $r=0.66$; S1xR: $r=0.33$). These findings indicate that the discharge of MEC cells generates a strong internally-organized representation of space that is intermittently and variably registered to external features of the environment, whereas the CA1 place cell representation of space is less robustly organized as assessed 1) within the hippocampal network, 2) with respect to MEC cells, and by any single feature of the external environment, even during effective navigation.

28. Victor Pedrosa, Imperial College London

Even before the first exploration, future place cells and future spatially untuned silent cells can be distinguished by their intrinsic properties. Manipulating these properties can switch a silent cell into a place cell. Additionally, silencing all place cells in a familiar environment has been shown to unveil a new subset of previously quiet cells, enabling the emergence of a new place map. Although vastly explored experimentally, the mechanisms underlying place field development and remapping are not fully understood. Using a computational model, we show how a simple inhibition-mediated network of neurons can lead to the emergence of two subsets of cells: active place cells and spatially untuned silent cells. We study how the suppression of place cells leads to a rapid and transient emergence of a new place map. Using a Hebbian-like plasticity model, we illustrate how this new place map can be stabilized with the repeated suppression of the initially active cells. Moreover, we propose an input-dependent inhibitory plasticity rule. When combined with heterogeneous, sparse connections, this rule leads to a rapid—but not instantaneous—place map shift while maintaining global neuronal activity. Our study provides a possible mechanism for place map plasticity in the hippocampal CA1 network.

29. Steven Poulter, Durham University

Memory for space-defining cues: trace responses in Boundary Vector CellsBoundary vector cells (BVCs) in the subiculum have provisionally been characterised as spatial perceptual cells due to apparently experience-independent, context-insensitive, spatial responses to boundary cues: e.g. a given BVC would respond broadly similarly across first or late exposures, across different boundary types (wall or cliff edge) and different spatial contexts (Lever et al, 2009; Stewart et al., 2014). Here we present data demonstrating not only that BVCs respond to a range of space-defining cues, including 'objects', when these are introduced into the local environment, but also that some BVCs maintain specific firing to locations where cues were located on the previous trial(s). BVC responses were independent of object identity and, as predicted by BVC models (e.g. Hartley et al., 2000), varied in their preferred distance tuning. These data support the notion of a boundary vector coding system in support of spatial memory.

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30. Michaela Pröll, LMU Munich

Grid-cell activity on linear tracks indicates purely translational remapping of 2D firing patterns at movement turnsMichaela Pröll, Stefan Häusler and Andreas V.M. HerzVarious types of neurons support spatial navigation. Their response properties are often studied in reduced settings and might change when the animal can freely explore its environment. Grid cells in rodents, for example, exhibit seemingly irregular firing fields when animal movement is restricted to a linear track but highly regular hexagonal patterns in two-dimensional arenas. Measured along one running direction only, firing fields are, however, compatible with a slice through a two-dimensional hexagonal pattern. It is an open question, whether this is also true if left-ward and right-ward runs are jointly considered. Here, we show that a single hexagonal firing pattern explains the linear-track data if translational shifts of the pattern are allowed at movement turns. A rotation or scaling of the grid is not required. The agreement is further improved if the peak firing rates of the underlying 2D grid fields can vary from field to field, as suggested by recent studies. These findings have direct consequences for experiments using linear tracks in virtual reality.

31. César Rennó-Costa, Federal University of Rio Grande do Norte

Place and grid cells have different codes for space. Based on the anatomy of the entorhinal-hippocampal circuitry, we constructed a model of place and grid cells organized in a loop to investigate their mutual influence in the establishment of their codes for space. Using computer simulations, we replicated various experiments that induced hippocampus remapping and assessed which features of the model account for the phenomena observed in neurophysiological data. We found that the interaction between grid and place cells converges quickly; the spatial code of place cells does not require, but is altered by, grid cell input; plasticity in sensory inputs to place cells is key for pattern completion but not pattern separation; grid realignment can be explained in terms of place cell remapping as opposed to the other way around; the switch between global and rate remapping is self-organized; and grid cell input to place cells helps stabilize their code under noisy and/or inconsistent sensory input. We conclude that the hippocampus-entorhinal circuit uses the mutual interaction of place and grid cells to encode the surrounding environment and propose a theory on how such interdependence underlies the formation and use of the cognitive map.

32. David Rowland, NTNU/Kavli Institute

Layer II of the medial entorhinal cortex (MECII) contains two principal cell types: pyramidal cells and stellate cells. Accumulating evidence suggests that these two cell types have distinct molecular profiles, physiological properties, and connectivity. Together, these observations hint at a fundamental functional difference between the two populations, but the currently available data lead to mixed conclusions, with some studies suggesting that stellate cells make up a large percentage of grid cell population and others suggesting that stellate cells are almost never grid cells. Here we used a tta-based transgenic mouse line to drive expression of ArchT, an optogenetic silencer, in stellate cells. By delivering short pulses of light over thousands of trials we were able to optogenetically identify stellate cells and characterize their functional properties. The stellate cell population included cells from every functional cell class as well as cells that did not fall into a functional category. Notably, roughly 1 in 4 of the identified cells were grid cells. These results indicate that the stellate population is heterogeneous but includes a large number of grid cells.

33. Nacho Sanguinetti Scheck, Humboldt University

The rat parasubiculum is an understudied parahippocampal structure engulfing the medial entorhinal cortex (MEC). It outputs to layer 2 of the MEC, targeting the calbindin positive patches (Tang et al., 2016). This puts the parasubiculum in a prime position to shape both spatial and temporal coding in the MEC.In this preliminary study we investigated Head Direction cells and Grid Cells of the parasubiculum in the presence of the animal's home cage. Unlike cells in the MEC these have not been scrutinized for their context dependency or their robustness to changes in the internal structure of the environment. We recorded Head Direction cells (n=37) from the Parasubiculum of rats (n=3). We found that in all cells the introduction of the home cage did not alter their head-directional preference. Translations and rotations of the home did not change (n=12 cells) the preferred head direction either.We recorded Grid cells from parasubiculum and MEC (n=32) and observed that in several instances, single firing fields shifted towards the location of the home or other internal structures of the environment. This could have implications for the role of Grid cells in path integration and in spatial coding of more complex environments.

34. Diogo Santos-Pata, SPECS, IBEC, UPC, UB

Awake hippocampal sharp-wave ripples (SWR) occur during stationary periods before initiation of movement towards a target location. Place-cells included in SWRs temporally fire in a coherent spatial order as observed during navigation and are correlated with future trajectories, suggesting that SWR sequences are part of a spatial decision-making process.De novo sequences found during sleep SWRs are recruited in future environments, suggesting that neuronal templates are built to serve future navigation. However, the mechanism by which SWRs sequences towards specific target locations are triggered is still unclear. Medial prefrontal cortex (mPFC) and CA1 coherence increases during SWR events, and projections to CA1 carry a target signal, suggesting that mPFC might play a role in selection of sequences for spatial sampling. In this study, we developed a spiking model with the anatomical and physiological constrains of the CA3 region and tested whether recent insights regarding goal signals, network specifics and SWRs properties are sufficient to sample possible 'representational routes' towards a target location. Our results suggest that when current and goal neurons are triggered, sampling of correct, but not misleading, sequences emerge autonomously. Parametrically quantification of our network match with physiological insights.

35. Ayelet Sarel, Weizmann Institute of Science

To navigate, animals need to represent their own position and orientation, but also the location of their goal. Neural representations of the animal's position and orientation were extensively studied. However, it is unknown how navigational goals are encoded in the brain. We recorded from hippocampal CA1 neurons of bats flying in complex trajectories towards a spatial goal. We discovered a subpopulation of neurons with angular tuning to the goal-direction (Sarel et al., Science, 2017). Many of these neurons were tuned to an occluded goal – suggesting goal-direction representation is memory-based. We also found cells that encoded distance-to-goal, often in conjunction with goal-direction. The goal-direction and goal-distance signals comprise a vectorial representation of spatial goals – suggesting a novel neuronal mechanism for goal-directed navigation.

36. Ben Towse, UCL

Grid patterns orient adaptively in polarised environmentsIn an environment with polarising spatial cues, the quality of information available for self-localisation is anisotropic. Using a biologically-inspired neural model, we investigated how an ensemble of grid cell modules could make the best of limited sensory information to maximise the fidelity of neural representations. We showed that self-location is decoded with the lowest fidelity when the grid pattern has one axis aligned with the environmental axis of greatest spatial uncertainty, and highest fidelity when it is maximally misaligned (30 offset). This result was consistent while other parameters of the grid cell ensemble were varied. We therefore predicted that in a polarised environment, grid cell patterns would orient in this way, optimising their representation of self-location. fMRI analyses of human subjects virtually navigating a polarised environment confirmed this prediction, finding that grid orientation, inferred from hexadirectional modulation of entorhinal BOLD activity, misaligned with the least informative axis. Thus we demonstrated experimentally that the entorhinal grid system orients adaptively to optimise performance in uncertain conditions.

37. Xudong Wang, Oxford University

Understanding the relationships between states in a task allows for quick and flexible inference on the basis of sparse observation. Such relational reasoning requires the representation of latent states which, although being unobservable, play a key role in enabling subjects to quickly predict changes of observable states before experiencing them. However, little is known about how the neural codes of latent states are built and represented in the brain. We recorded the spiking activities of multiple neurons by wireless silicon probes in mPFC and lOFC while the rats learned a cognitive map of auditory cues which are either anti-correlated or uncorrelated in reward probabilities. After poking to initiate a cue in each trial, the rat can either choose to press the lever to reveal whether the cue is rewarded, or choose to re-poke the port to initiate the next cue. We found the rats could learn about the anti-correlated relationship between two cues and guide their choice using this knowledge of latent state. And our preliminary neural analyses showed that the population neural responses at the outcome time could reflect the rat's current belief about the relationship between cues.