space and time in the brain – cogs260 – Nitz – spring, 2011

week 4 – allocentric space, head-direction cells, border cells, grid cells, place cells, speed registration, context registration

“We’re not lost…we’re right here” – Arthur Schmidt (circa 1979)
week 10 free for all / blitz of oddities and illusions?

- snapshot consciousness
- space in memory and reality
- Einstein’s brain
- tool use / extended personal space – Luke Miller
- body dysmorphic disorder – Luke Miller
- Steiner lines
- hemineglect
- the binding problem
- the pinocchio effect
- internal alarm clocks
- the pineal gland
- prism adaptation
- crossover of space, time, and language – Tyler Marghetis
- backwards causation – Tyler Marghetis
- the man who lost his body
- temporal discounting
- the distal reward problem
- territorial / social space
- homing pigeons and electromagnetic space
- bee directions
- Picasso / Pollock / Dali / Van Gogh
- cross-generation navigation (butterflies)
- ants navigation / dead reckoning – Doug Nitz
- bird caching of food
starting at the end (because they were discovered first) – place cells

place cells are neurons, found only in the hippocampus, whose action potential generation is restricted to the presence of the animal in a particular region of the environment

frequently asked questions:

does place-specific activity persist in the dark?
what defines the space of an environment?
is place field activity direction-dependent?
how big are place fields?
are place fields everywhere in an environment?
are place cells (and/or their fields) topographically organized?

O’Keefe and Dostrovsky, Brain Research, 1971
the ‘space of the environment’ may be defined a number of ways and a number of definitions may exist simultaneously (i.e., the population of hippocampal neurons may map more than one ‘space’ at a time.

Gothard et al., J. Neuroscience, 1996
Markus et al., J. Neuroscience, 1995
dorsal hippocampal neurons have rat-sized place fields (including the tail) while ventral hippocampus neurons may have 5 meter-long fields.

Kjelstrup et al., Science, 2008
for the most part, place cell fields distribute evenly throughout an environment and reliably appear in the same places across different run sessions
neighboring place cells (recorded on the same wire) show no tendency to fire in similar places

Redish et al., J. Neuroscience, 2001
generally, the relative positioning of place fields for two neurons in one environment is not related to their position in another.

Leutgeb et al., Science, 2004
discovery #2 - head-direction cells – neurons whose firing is specific to particular head orientations of the animal (relative to the environment)

Taube et al., J. Neuroscience, 1990
a potential network architecture supporting head-direction cell activity among a population of neurons: combining specific patterns of connection strengths with an angular motion signal (CW vs. CCW)

Figure 1 | One-dimensional attractor map model for head direction encoding based on neural integration of head angular velocity signals. a) Head direction cells are arranged symbolically in a circle in order of their relative head directional preferences. Each cell (coloured dots) connects with nearby cells with a synaptic strength (or connection probability) that declines as a function of distance (red and grey lines). The network is subject to global feedback inhibition (not illustrated) that limits the total neural activity. Activity in such a network has a most probable configuration in which the activity is focused at one point and declines with distance from that point (warm colours represent high activity, progressively cool colours represent progressively lower activity). Such a network would keep track of head direction if the hill or ‘bump’ of activity could be made to rotate around the ring in correspondence with changes in head direction. b) Rotation of the bump in the clockwise or anticlockwise directions can be achieved by an intermediate group of two types of conjunctive neuron that receive information about head angular velocity from the vestibular system (dashed arrows) and information about current head orientation from the cells immediately above them in the outer ring. The intermediate group of cells must be of two classes: cells receiving information about clockwise motion project to the right of the cells in the outer ring from which they receive input, whereas cells receiving anticlockwise vestibular signals project to the left. These hidden layer cells drive the activity bump in the corresponding direction around the ring. In the absence of motion, activation of all hidden layer cells is assumed to be below threshold. In this figure, only active connections are indicated, with the line thickness representing firing rate.

McNaughton et al., Nature Reviews Neuroscience, 2006
extending the idea – place cell activity in a network wherein connection strengths (in 2 dimensions) are combined with head-direction inputs

Figure 2 | Extension of the one-dimensional attractor map concept to two dimensions: a model for path integration. Neurons arranged in a plane (a) have interconnections that decline in strength (or probability) monotonically with distance (red arrows). Notice that a boundary problem exists for connections near the edge of the layer of neurons. A solution for this problem is illustrated in FIG. 3. Global feedback inhibition (not shown) keeps the net activity within a narrow range, leading to a focused spot or 'bump' of activity somewhere in the plane (b). The bump can be made to move in correspondence with a rat's motion using an intermediate layer of cells that are conjunctive for position on the plane and head orientation, if the activity of these cells is positively modulated by running speed and the cells encoding a given head direction project asymmetrically to the corresponding side of the cells in the attractor layer from which they receive input. The thresholds are arranged so that these hidden layer cells are silent when there is no motion.
dorsomedial entorhinal cortex neurons (making up a major input to the hippocampus) exhibit multiple firing fields in any given environment. The creation of a spatial autocorrelation from their firing ratemaps reveals the distinct geometric relationships between the positioning of the fields. Fields are arranged along the nodes of a group of tessellated triangles.

Hafting et al., Nature, 2005

Figure 1 | Firing fields of grid cells have a repetitive triangular structure. a, Sagittal Nissl-stained section indicating the recording location (red dot) in layer II of the dMEC. Red line indicates border to postrhinal cortex. b, Firing fields of three simultaneously recorded cells at the dot in a during 30 min of running in a large circular enclosure. Cell names refer to tetrode (t) and cell (c). Left, trajectory of the rat (black) with superimposed spike locations (red). Middle, colour-coded rate map with the peak rate indicated. Red is maximum, dark blue is zero. Right, spatial autocorrelation for each rate map (see Supplementary Methods). The colour scale is from blue ($r = -1$) through green ($r = 0$) to red ($r = 1$). c, Box plot showing distribution of angles ($\phi_1$, $\phi_2$ and $\phi_3$) between the central peak of the autocorrelogram and the vertices of a hexagon defined by the nearest six peaks. The diagram shows median angles (horizontal lines inside boxes), interquartile distances (boxes), upper and lower limits, and outliers (horizontal lines). d, Discharge maps (as in b) showing similar triangular structure in enclosures of different size (left, large; middle, small; right, large).
grids! – the nodes of grid cells recorded in dorsal regions of the dorsomedial entorhinal cortex are spaced more closely than those of grid cells recorded in ventral regions.

the orientation of grids relative to the environment is shared by neighboring neurons.
neighboring neurons have similar grid orientations (relative to the environment) and similar grid node spacings, but grid nodes are nevertheless offset (and in a random fashion)

not shown is that offsets of grid node placements persist in different environments

not shown is that increasing the size of an environment increases the number of nodes rather than increasing the size of the nodes (i.e., grid space is absolute)

in this way, the grid cell network differs from the place cell network – grid nodes for different neurons always have the same spatial relationships (i.e., the map is generic to all environments or ‘universal’)

Hafting et al., Nature, 2005
grids! – dorsomedial entorhinal cortex also contains a population of head direction cells

Sargolini et al., Science, 2006

grids! – dorsomedial entorhinal cortex also contains a population of ‘conjunctive’ cells whose grid-like activity is only observed for particular head-directions – notably, these cells are especially speed-sensitive

Sargolini et al., Science, 2006
a revised look at the origin of place-specific activity: place cells from grid cells

Figure 6 | Combining multiple periodic grids at different spatial scales can result in non-periodic place fields. a) The effects of slight variation in grid scale (6% in this case) on the periodicity of a mapping space defined by the superimposition of the output of two grid modules. In general, the summation of two periodic signals that differ in frequency gives rise to a signal with amplitude maxima that occur with a much lower frequency (the difference between the fundamental frequencies). b) Multiple grid fields with different scales, as expressed by cells at different dorsoventral levels of the medial entorhinal cortex can be combined for example, by linear summation, resulting in an activity field that has only one large maximum. The spatial frequency of the patterns increases systematically from left to right. A simple thresholding operation applied to the summed grid fields (here implemented by a sigmoidal function shown in red) yields a field that is restricted to a region of space. This is a potential mechanism for the generation of non-periodic place fields such as those observed in the hippocampus.
In 1952, Alan Turing\textsuperscript{1} proposed a mechanism for how structures could emerge spontaneously in chemical systems, and suggested that such a mechanism could underlie pattern formation in nature (that is, morphogenesis). In the proposed mechanism, diffusion-driven instabilities could occur in a homogeneous mixture of chemically reacting species, producing spatially periodic patterns. The chemical reactions considered involve an auto-catalytic activator species. The increase in the activator provokes the increase in a counter-balancing inhibitory species. A crucial requirement for the Turing instability is that the diffusion rate of the inhibitor is larger than that of the activator; this allows for local growth of the activator being limited in its spread by the faster diffusing inhibitor. This scheme will repeat itself in the spatial domain, eventually producing structures with a characteristic wavelength. Although the Turing instability has been studied intensively in theory, it was in 1990 that Castets et al.\textsuperscript{,37} managed to experimentally produce the Turing pattern in a chemical system. They used the chlorite-iodide-malonic acid (CIMA) reaction, in which iodide and chlorite are the activator and the inhibitor, respectively. Castets et al. performed the reaction in a gel loaded with polyvinylalcohol, which is a macromolecule that has a slow diffusion rate. Importantly, the macromolecule partly binds the iodide, effectively slowing down the diffusion of the activator. Under these conditions, Turing structures emerged spontaneously in the gel. Depending on the reaction parameters, the emergent patterns consist of either regular grids, reminiscent of medial entorhinal cortex grid fields (panel a), or stripes (panel b), reminiscent of ocular dominance bands in the visual cortex. Neural networks consisting of mutually excitatory principal cells and feedback inhibitory cells can produce such Turing instability as well, by making the range of inhibitory connections longer than the excitatory ones. Figure reproduced, with permission, from REF. 138 © (2002) World Scientific.

McNaughton et al., Nature Reviews Neuroscience, 2006
border cells (discovery #4)

these neurons are also found in the dorsomedial entorhinal cortex – they maintain firing against borders (usually one) of an environment expansion of the dimension of an environment corresponding to a border neuron expands its firing in that dimension – expansion in another dimension does not...
remapping – the mechanism that allows the hippocampus to map not only individual places but to create unique maps for each environment and different maps for the same environment.

remapping highlights the fact that all allocentric mappings (place, grid, head direction, border) are magically ‘anchored’ to the reference frame of the environment.

how? – perhaps a contribution from border cells? – perhaps a contribution from lateral entorhinal cortex?
Figure 1  Grid fields repeat across arms with similar running directions. (a) Experimental protocol. The rat ran for 20 min in the open field, followed by two 20-min runs in the hairpin maze and another 20-min run in the open field. Between runs, the rat rested in its home cage or on a towel in a flower pot next to the maze. Horizontal bar indicates cue card. Right is east, left is west, top is north and bottom is south. (b–d) Three different cells are shown, one in each row (b, layer II/III; c, layer III; d, layer III). Alternating columns show trajectories with individual spike locations and color-coded rate maps. Trajectories are black and spike locations red. Walls are marked in green. The color code in the rate maps is from blue (silent) to red (peak rate), with the color scale maximum indicated beneath the rate map. The left pair of columns shows the first trial in the open field, the next two pairs show eastbound and westbound trajectories (arrows indicate running direction), respectively, in the hairpin maze, the right pair shows the second trial in the open field. Although clear grid fields were apparent in the open field, the grid broke up in the hairpin maze. Note the repetitive firing pattern across arms with similar running directions.
Box 1. Anatomy of the hippocampal formation

We present here a simplified sketch of the connections between the neocortex, the parahippocampal regions (PHR) and the hippocampal formation (HF) (Figure I). For a more comprehensive and detailed description see Witter and Amaral [88]. The neocortex is connected to the hippocampus mainly via two pathways through the parahippocampal cortex. One projects through the perirhinal cortex (PER) and the lateral entorhinal cortex (LEC); the other projects through the postrhinal cortex (POR) and the MEC. Cells that carry information about the position of the animal, such as grid cells, head direction cells, and border cells, are found in MEC but not in LEC [30]. MEC and LEC project to the same regions in the hippocampus, both via direct projections to each hippocampal subfield and via the indirect trisynaptic circuit through dentate gyrus and CA3. While axons from MEC and LEC to dentate gyrus and CA3 tend to target the same cells, connections to CA1 are split, such that MEC is linked preferentially to the proximal part of CA1, and LEC preferentially to the distal part. This differential connectivity leads to stronger spatial modulation in proximal than distal CA1 [89]. The arrow from CA3 to itself stresses the abundance of recurrent connections within area CA3. Signals are routed back from CA1 to the entorhinal cortex either via direct projections, or via the subiculum (Sub), the presubiculum or the parasubiculum (not shown in Figure I).

Figure I. Major anatomical connections in the HF and PHR. Reproduced with permission from [30].

Derdikman and Moser, Trends in Cognitive Sciences, 2010
remapping can be dynamic

Kelemen and Fenton forced rats to avoid two different regions of a rotating arena (lest they be shocked)

one region rotated with the arena itself – one region occupied ever-changing regions of the arena but the same region of the surrounding, non-rotating room

place fields from different neurons mapped either position in the arena or position in the room

repeated transitions between ‘room-frame’ neurons and ‘arena-frame’ neurons were observed