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Field repetition and local mapping in the hippocampus and medial entorhinal cortex

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1 **Abstract**

2 Hippocampal place cells support spatial cognition and are thought to form the neural
3 substrate of a global 'cognitive map'. A widely held view is that parts of the hippocampus also
4 underlie the ability to separate patterns, or to provide different neural codes for distinct
5 environments. However, a number of studies have shown that in environments composed of
6 multiple, repeating compartments, place cells and other spatially modulated neurons show the
7 same activity in each local area. This repetition of firing fields may reflect pattern completion,
8 and may make it difficult for animals to distinguish similar local environments. In this review we
9 will (a) highlight some of the navigation difficulties encountered by humans in repetitive
10 environments, (b) summarise literature demonstrating that place and grid cells represent local
11 and not global space, and (c) attempt to explain the origin of these phenomena. We argue that
12 the repetition of firing fields can be a useful tool for understanding of the relationship between
13 grid cells in the entorhinal cortex and place cells in the hippocampus, the spatial inputs shared
14 by these cells, and the propagation of spatially-related signals through these structures.

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25 How locations in the outside world are represented in the brain has been a topic of
26 intense research interest for almost 50 years, since the discovery of neurons in the rodent
27 hippocampus - place cells - which fire in individual places in an environment (O'Keefe and
28 Dostrovsky 1971). Following O'Keefe and Nadel's (1976) conceptualisation of the hippocampus
29 as a cognitive map, much of the ensuing work has assumed that place cells comprise a
30 representation of the entire environment in which the animal finds itself (though different
31 reference frames are possible within this map, e.g. Poucet 1993; Gothard et al. 1996; Zinyuk et
32 al. 2000). In the current review, we challenge this assumption of a global map in light of data
33 indicating that many spatial cells are driven by local boundaries and a directional input. These
34 influences provide an allocentric encoding of local spaces, which is only incidentally global.

35 Space is traditionally defined from two reference points. In the first, location within an
36 environment is defined using 'self-relative' directions, such as "on my left" or "20 feet in front of
37 me". This is egocentric space. In the second, locations are identified independent of the
38 observer, for "halfway between the window and the door" or "behind the chair and towards the
39 painting". This is allocentric space. In the current review we are primarily concerned with how
40 the latter is represented in the brain.

41 In humans, representations of space likely vary in terms of their scale and detail. For
42 instance, a person can recognise their location within a given room of their house, but also,
43 simultaneously, where they are within a geographical region. Thus, different types of spatial
44 representations may operate, depending on the task at hand (Burgess 2006; Ekstrom et al.
45 2014). In the present review, we restrict our consideration to allocentric space as it is
46 represented by (or as it correlates with) the firing fields of spatially tuned neurons in the rodent
47 brain. Identifying the rules by which these operate may allow us to understand the interplay
48 between location recognition and longer-range navigation.

49 Whether the mammalian brain maps space in local or global coordinates is an important
50 issue because it likely constrains spatial cognition. From this perspective, there is evidence that
51 certain types of spaces, such as repetitive local geometries, are more challenging than others
52 for wayfinding. For example, city planners are discouraged from using repetitive street designs
53 as they are considered disorienting (Rumbarger and Vitullo 2003). This effect is embodied in the
54 repetitive streets of Brasília, which are challenging to navigate (Scott 1998). Difficulties in
55 distinguishing locations can also be problematic for patients suffering from dementia. Such
56 individuals can find long corridors confusing, especially those with repetitive elements (Netten
57 1989; van der Voordt 1993). There is also evidence that patients prefer 'L' shaped corridors to
58 long straight ones (Elmståhl et al. 1997; Marquardt 2011; Passini et al. 2000; Rainville et al.
59 2002). As we will consider below, such observations are consistent with the responses of
60 spatially tuned neurons in the rodent brain to repetitive local environments.

61 Place and grid field repetition

62 In the traditional view of place cells, each cell exhibits a unique firing field and together
63 these place fields represent the animal's entire environment (e.g., Barnes et al. 1997; see
64 Figure 1). One approach to studying place cells and other types of spatially-tuned neurons has
65 been to manipulate the animal's environment and see how this affects firing fields (e.g., Muller
66 and Kubie, 1987; Bostock et al. 1991; O'Keefe and Burgess 1996; Lever et al. 2002; Leutgeb et
67 al. 2004; 2005; Barry et al. 2007; Chen et al. 2013; Krupic et al. 2015; Acharya et al. 2016). A
68 second approach has looked at these cells during purposeful behavior. This work has shown
69 that place cell firing is modulated by task demands (e.g., Markus et al. 1995; Wood et al. 2000;
70 Moita et al. 2004; Hok et al. 2007), and by the internal state of the animal (Kennedy and Shapiro
71 2004; 2009; for review see Schiller et al. 2015). From the perspective of the hippocampus at
72 least, the latter approach has indicated a function beyond the representation of space. In the

73 ensuing discussion, however, we limit our consideration to studies focussing on the changes to
74 the animal's environment, though we acknowledge that the addition of task demands also
75 influences place cell firing correlates.

76 Within this domain, several findings suggests that when rats move between two or more
77 similar maze rooms, a given place cell produces the same field in each room. For instance,
78 Skaggs and McNaughton (1998) recorded dCA1 place cells while rats explored an environment
79 composed of two identical compartments joined by a corridor. They found that place cells often
80 showed similar firing fields in each of the two compartments (Figure 2A; see also Fuhs et al.
81 2005). Thus, instead of having unique representations of each compartment, as one would
82 predict for a mapping of the entire environment, many place cells showed similar fields across
83 compartments. The lack of remapping observed between compartments suggests that place
84 cells are partly driven by local views.

85 In an elegant extension of the Skaggs and McNaughton study, Spiers et al. (2015)
86 recorded dCA1 place cells as rats moved between four parallel maze compartments connected
87 with an alleyway. They found that individual place cells tended to show similar place fields in all
88 four compartments (Figure 2B). Cells only formed a distinct representation for a specific box
89 when its size or colour was changed, and even in this case repetition of fields was found in the
90 remaining three boxes. These findings were replicated by Grieves et al. (2016), as will be
91 described below.

92 A similar phenomenon has been observed in grid cells - neurones from the entorhinal
93 cortex, pre-, and post-subiculum which exhibit multiple, regularly arranged fields within an
94 environment (Hafting et al. 2005; Figure 1). For example, Derdikman et al. (2009) recorded
95 from grid cells and place cells in a zigzag alleyway, or 'hairpin' maze and found that both types
96 of cell showed firing fields that repeated across alleyways facing the same direction (Figure 2C).
97 These fields did not repeat across alleyways that the animal entered in the opposite direction.

98 Repeating, local representations persisted regardless of the large number of alleyways (five in
99 each direction), suggesting that self-motion information, such as distance travelled, did not
100 inform the activity of these cells. The authors refer to this phenomenon as a ‘fragmentation’ of
101 the firing fields.

102 Repetition/fragmentation of firing fields depends on direction

103 An important finding from Derdikman et al.’s (2009) hairpin maze experiment was that
104 place and grid cell fields were modulated by the heading direction of the animal. Cells
105 differentiated North facing compared to South facing alleyways and the position of fields was
106 also dependent on the direction with which the rat ran through the maze (Figure 2C). As the zig-
107 zag route through the maze was continuous, the most parsimonious explanation for this finding
108 is that the spatial cells were sensitive to the animal’s allocentric direction (e.g., McNaughton et
109 al. 1983; Muller et al. 1994), as opposed to alternating between different motivational states
110 (Smith and Mizumori 2006).

111 Supporting this interpretation, Whitlock and Derdikman (2012) recorded from mEC
112 layers II, III and V and showed that head direction cells, neurones in an interconnected series of
113 brain regions that are tuned to individual allocentric directions (Taube et al., 1990a), maintained
114 a stable firing direction throughout this apparatus. The head direction system is a defining input
115 to both place cells and grid cells (Leutgeb et al. 2000; Zhang et al. 2013; Acharya et al. 2016;
116 Peyrache et al. 2016; Winter et al. 2015; see also Rubin et al. 2014), one possibility is that such
117 a directional input provides an invariant directional reference which contributes to repetition of
118 spatial fields when an animal repeatedly faces the same direction across maze compartments.
119 In this view, the head direction system provides a global reference frame across maze
120 compartments (e.g., Taube and Burton 1995). This maintenance of orientation across

121 compartments likely requires self-movement of the animal between compartments; when a rat is
122 passively moved between different compartments or local features, the preferred firing direction
123 of its head direction cells can switch from room to local cue anchors (Stackman et al. 2003;
124 Taube et al. 2013)

125 The notion that a directional input to place cells is also supported by findings from Nitz
126 (2011), who recorded dCA1 place cells in an alleyway which spirals inwards to a point. The cells
127 had multiple fields in coils of the spiral that have the same angular relation to the centre and
128 which face the same direction (Figure 3B). Furthermore, as in Derdikman et al.'s (2009) hairpin
129 maze, cells fired differently depending on the direction of travel through the alleyway. This is
130 consistent with the finding of Fuhs et al. (2005) in a multicompartiment environment. They
131 replicated the two box apparatus of Skaggs and McNaughton (1998), but also recorded dCA1
132 place cells in the same two compartments joined end to end and connected directly by a
133 doorway (Figure 3A). When the compartments were connected by a corridor, place cells
134 showed the same activity in each. However, when the compartments were connected directly to
135 one another, the cells formed a different representation for each compartment. Importantly, in
136 the latter, the doorways are in different relative positions (South in one compartment, North in
137 the other), whereas in the corridor situation the doorways are in the same position for both (e.g.,
138 West).

139 The results of Tanila (1999) are consistent with these findings. Tanila recorded dCA3
140 place cells in a similar apparatus – two compartments connected directly by a doorway. Similar
141 to the results with CA1 cells, 91% of the place fields in CA3 cells differed between
142 compartments. Again, as the rats actively moved between the compartments, it is likely that the
143 doorway between the two served as a distinguishing landmark.

144 To directly assess the impact of compartment orientation as a distinguishing cue,
145 Grieves et al. (2016) recorded place cells in a four compartment apparatus similar to the one

146 used by Spiers et al. (2015). In addition to this 'parallel' configuration, an alternative maze was
147 used where a 60° angle was introduced between the compartments (Figure 3C). The same
148 actual compartments were used in both situations, and they differed only in their orientation and
149 the shape of the connecting alleyway for each. In the parallel configuration, dCA1 place cells
150 fired similarly in every compartment, as observed by Spiers et al. (2015). However, similar to the
151 results of Fuhs et al. (2005), when compartments were at a 60° angle to one another, place field
152 repetition was not observed. These results again suggest that directional reference allows place
153 cells to disambiguate otherwise visually and geometrically identical local environments.

154 Repetition of spatial fields may constrain spatial learning

155 As noted earlier, human navigation performance decreases as directional and geometric
156 cues become invariant, such as in long repetitive corridors or streets (Marquardt 2011). Might
157 repetition of the activity of spatial cells underlie such difficulties in navigation? To test this,
158 Grieves et al. (2016) trained naïve animals on a conditional odor discrimination task in either the
159 parallel or radial version of their four compartment maze (Figure 3C). In this task, an identical
160 set of four odorised sand wells was present in each box and a different odor was rewarded in
161 each one. Thus, rats had to discriminate between the compartments to find the food efficiently.
162 In the parallel configuration, where field repetition was found, animals were significantly
163 impaired in learning compared to the group trained in the radial configuration where field
164 repetition was absent. These results suggest that local environments in which place field
165 repetition is observed are more difficult for animals to discriminate compared to those in which
166 place field repetition is not observed. Although it was not examined in the Grieves et al.
167 experiments (where separate rats were used in the recording and behavioral experiments), it is
168 also possible that learning to discriminate maze compartments yields more unique place cell

169 fields across compartments.

170 Can a bias towards local mapping be overcome with experience? Although rats in the
171 Grieves et al. (2016) study were impaired in parallel compartments, some did eventually learn
172 the task. Thus it is possible that with repeated experience of connected environments, a global
173 representation replaces local maps. A recent study by Carpenter et al. (2015) provides evidence
174 for this. They recorded grid cells in the mEC as rats explored two parallel, connected
175 compartments similar to those of Skaggs and McNaughton (1998) although larger (90cm
176 instead of 60cm square) in order to reveal the grid firing structure. During initial exposure to this
177 environment, grid cells often fired similarly in both compartments. However, after multiple
178 exposures to the environment, cells tended to possess fields that formed a continuous grid
179 across the two compartments (Figure 4A). This suggests that, with experience, the encoding of
180 local compartments gives way to a representation of the entire enclosure. Whether this slow
181 change in grid firing is accompanied by a change in place cell activity is not known, although
182 such a relationship has been observed in other experiments (Fyhn et al. 2007; Jeffery 2011). If
183 grid and place cells behave similarly, it might also be predicted that grid fields are less local in
184 compartments that face different directions.

185 In contrast to the spatial deficits reported by Grieves et al. (2016) and the gradual
186 transformation towards a global map reported by Carpenter et al. (2015), some research
187 suggests that a form of place field repetition increases with spatial learning. This evidence
188 comes from studies by Frank et al. (2000, 2001) and Singer et al. (2010), where the activity of
189 spatial cells while animals navigated mazes composed of multiple, parallel alleyways. As in
190 Derdikman et al.'s (2009) hairpin maze, dCA1 and dCA3 place cells and neurons in the
191 entorhinal cortex (superficial and deep layers of mEC) fired similarly in multiple alleyways
192 (Figure 4B). Furthermore, these representations were also dependent on the direction of the
193 animal's movement. In agreement with the view of the hippocampus as a pattern separator, this

194 field repetition was observed more in EC neurons than in hippocampal place cells. Frank et al.
195 (2000, 2001) and Singer et al. (2010) termed this field repetition ‘path equivalence’ and
196 suggested that it represents encoding of the relationship between behaviour and location. In
197 support of this, the frequency of path equivalence appeared to increase as animals learned a
198 task (Figure 4B). To account for this, it may be speculated that in well learned tasks, spatial
199 cells also begin to reflect common elements of different paths, perhaps via inputs from regions
200 such as the retrosplenial cortex (e.g., Alexander and Nitz 2017).

201 Visual, geometric, and directional inputs to spatial cells

202 Due to the strong control the geometry of the environment has over place cell activity
203 (O’Keefe and Burgess 1996; Barry and Burgess 2007; Lever et al. 2002; see Figures 2D, 5A
204 and 5B), it has been proposed that place fields arise from the activity of cells sensitive to
205 boundaries, termed “Boundary Vector Cells” (BVCs) (Barry et al. 2006; Hartley et al. 2000).
206 These cells were originally predicted to be sensitive to boundaries at a specific direction and
207 distance from the animal (Figure 5C). Actual cells resembling BVCs were subsequently
208 observed in the subiculum (Barry et al. 2006; Lever et al. 2009; Solstad et al. 2008; Broton-Mas
209 et al., 2017) (Figure 1 and 5D), the presubiculum and parasubiculum (Boccaro et al. 2010), the
210 mEC (Bjerknes et al. 2014; Savelli et al. 2008; Solstad et al. 2008) and recently in the anterior
211 claustrum (Jankowski and O’Mara 2015) and the rostral thalamus (Jankowski et al. 2015).
212 These ‘boundary cells’ are sensitive to walls, low ridges or even vertical drops (Figure 5C and
213 D) (Lever et al. 2009). The directional component of boundary cells is presumably informed by
214 the head direction system (Peyrache et al. 2016 but see Burgess et al. 2001; Byrne et al. 2007;
215 Julian et al. 2015). Importantly, in multiple, geometrically identical, similarly oriented
216 compartments the firing of a single boundary cell is expected to be identical (Carpenter et al.

217 2015; Lever et al. 2009). If place cells are driven by local borders (e.g., Zhang et al. 2014),
218 identical place fields would be observed in each compartment. In this view, as the angle
219 between identical compartments or alleyways increases, boundary cell firing should
220 correspondingly start to differentiate them. It is also possible, however, that other types of
221 spatially tuned neurons represent the shape of local environments (e.g., Broton-Mas et al.
222 2017), and thereby contribute to repetition of spatial firing fields.

223 As an alternative, visual inputs could account for spatial field repetition. If the corners of
224 a compartment or alleyway can function as visual cues, then parallel compartments or
225 alleyways may fall on the retina in similar patterns at the same head direction. If the angle
226 between these compartments is increased, however, this relationship will decrease. Thus, place
227 field repetition could arise from the congruence of visual and directional inputs. As with
228 boundary cells, neurons that are sensitive to a conjunction of head direction and position can
229 also be found in the retrosplenial cortex (Cho and Sharp 2001). Grid cells are also sensitive to
230 visual and olfactory contextual changes (Marozzi et al. 2015; Chen et al. 2016; Pérez-Escobar
231 et al., 2016) and changes in grid fields are correlated with remapping in place cells (Fyhn et al.
232 2007; Jeffery 2011; Monaco and Abbott 2011; Miao et al. 2015).

233 Are these inputs functionally different? Research suggests that there are differences in
234 how visual information and boundaries are used. Field repetition can be observed in
235 environments whether or not a distal visual cue is provided (Grieves et al. 2016; Derdikman et
236 al. 2009), if proximal cues are provided (Fuhs et al. 2005) and even in the dark (Grieves 2015).
237 This striking perseveration suggests that perhaps only local visual cues such as those utilised
238 by Spiers et al. (2015) are enough to drive pattern separation and overcome field repetition,
239 which would be suggestive of a contextual input, such as that from the entorhinal cortex. This is
240 supported by the finding that in many environments humans and animals primarily utilise
241 geometric information to orient themselves while ignoring contextual visual information (Cheng

242 1986; Hermer and Spelke 1994; Krupic et al. 2016; but see Learmonth et al. 2002; Hupback and
243 Nadel 2005). Furthermore, mice have been observed to utilise contextual visual cues to
244 recognise an environment, whilst continuing to make systematic heading errors, suggesting that
245 contextual and geometric information may be processed and utilised by two separate systems
246 (Julian et al. 2015). One possibility is that place cell firing is largely and primarily dictated by
247 geometric inputs from boundary cells, but that this input is mediated by a contextual input from
248 entorhinal cortex, similar to the contextual gating model proposed by Hayman and Jeffery
249 (2008).

250 The view proposed here is that on initial exposure to an environment, a rapid process is
251 initiated which relies heavily on geometric inputs from boundary cells to orient and arrange both
252 place and grid fields. In a repetitive environment these inputs are identical in each local area
253 and hippocampal pattern separation fails, resulting in repeating place fields. However, with
254 greater exposure to an environment, information accumulated through path integration drives
255 the repeating grid fields towards a global representation with low levels of field repetition
256 (Carpenter et al. 2015) and this development in turn could potentially drive increasingly global
257 (spatially unique) place fields. Evidence for rapid mapping based on geometry can be seen
258 when comparing the time scales at which spatial cells develop their firing patterns. In novel
259 environments boundary and head direction cells develop stable firing patterns instantaneously
260 (Jankowski et al. 2015; Taube and Burton 1995; Taube et al. 1990b), whereas hippocampal
261 place cells require 5-10 minutes to form stable place fields (Bostock et al. 1991; Frank et al.
262 2004; Hill 1978; Wilson and McNaughton 1993) and grid cells require a number of hours to
263 stabilise (Barry et al. 2012). Visual inputs also play an important role within this framework. For
264 instance, when large contextual changes occur within an environment, like the colour change of
265 a subcompartment, EC cells locally remap which allows for greater pattern separation in the
266 hippocampus in the altered compartment.

267

268

Remaining challenges

269 A central theme of this review is that place cells, and to an extent grid cells, are driven
270 by local boundaries and a directional input. If these are congruent across maze compartments,
271 repetition of firing fields is observed. This suggests that, at least initially, the mapping of
272 external, allocentric space in the mammalian brain is local, and not global.

273 Grid cell field fragmentation and place field repetition are strikingly similar, and would
274 appear to represent the same phenomenon. However, several questions remain. First, as place
275 fields are still present after grid cell firing is abolished (Brun et al. 2008; Hales et al. 2014), does
276 inactivation of the mEC affects hippocampal field repetition (or vice-versa)? Second, do inputs
277 from the subiculum, where many boundary cells reside, affect firing in either the mEC or the
278 hippocampus? Indirect evidence for this is found in work showing that grid cells may be
279 sensitive to border cell inputs (Hardcastle et al. 2015) and that lesions of the subiculum
280 contribute to spatial navigation deficits (Morris et al. 1990). Third, what effects does disruption of
281 the head direction system have on border/boundary cells (Burgess et al. 2001; Byrne et al.
282 2007)? Finally, does disruption of the head direction system affect place field repetition?

283 Given the framework of this review, without head direction input place cells should be
284 reduced to relying purely on visual inputs, assuming boundary cells require the head direction
285 system. Do grid cells immediately form a global representation in radial compartments as place
286 cells do and how do contextual changes in local compartments influence grid cells? One
287 prediction is that grid cells remap immediately following a compartment context change and that
288 this is accompanied by remapping in place cells, but this has yet to be shown in a
289 multicompartment environment. With a better understanding of these relationships we should
290 gain insight into processing between the hippocampus, the entorhinal cortex and the

291 surrounding structures. Ultimately, this may inform the design of repetitive environments to
292 minimize spatial ambiguity.

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295 **References**

296 **Acharaya L, Aghajan ZM, Vuong C, Moore JJ, Mehta MR.** Causal influence of visual cues on
297 hippocampal directional selectivity. *Cell* 164: 197-207, 2016.

298 **Alexander AS, Nitz DA.** Spatially periodic activation patterns of retrosplenial cortex encode
299 route sub-spaces and distance travelled. *bioRxiv* doi.org/10.1101/100537, 2017.

300 **Allen K, Gil M, Resnik E, Toader O, Seeburg P, Monyer H.** Impaired Path Integration and
301 Grid Cell Spatial Periodicity in Mice Lacking GluA1-Containing AMPA Receptors. *J*
302 *Neurosci*, 34: 6245–6259, 2014.

303 **Anderson MI, Jeffery KJ.** Heterogeneous modulation of place cell firing by changes in context.
304 *J Neurosci*, 23: 8827–8835, 2003.

305 **Barnes CA, Suster MS, Shen J, McNaughton BL.** Multistability of cognitive maps in the
306 hippocampus of old rats. *Nature*, 388: 272-275, 1997.

307 **Barry C, Burgess N.** Learning in a geometric model of place cell firing. *Hippocampus*, 17: 786–
308 800. doi:10.1002/hipo.20324, 2007.

309 **Barry C, Ginzberg LL, O'Keefe J, Burgess N.** Grid cell firing patterns signal environmental
310 novelty by expansion. *Proc Natl Acad Sci*, 109: 17687–17692, 2012.

311 **Barry C, Hayman R, Burgess N, Jeffery KJ.** Experience-dependent rescaling of entorhinal
312 grids. *Nat Neurosci*, 10: 682–684, 2007.

313 **Barry C, Lever C, Hayman R, Hartley T, Burton S, O'Keefe J, Burgess N.** The boundary
314 vector cell model of place cell firing and spatial memory. *Rev Neurosci*, 17: 71–97, 2006.

315 **Best PJ, Thompson LT.** Persistence, reticence, and opportunism of place-field activity in
316 hippocampal neurons. *Psychobiol*, 17: 236–246, 1989.

- 317 **Bjerknes TL, Moser EI, Moser M-B.** Representation of geometric borders in the developing rat.
318 *Neuron*, 82: 71–78, 2014.
- 319 **Boccaro CN, Sargolini F, Thoresen VH, Solstad T, Witter MP, Moser EI, Moser M-B.** Grid
320 cells in pre- and parasubiculum. *Nat Neurosci*, 13: 987–994, 2010.
- 321 **Bostock E, Muller RU, Kubie JL.** Experience-dependent modifications of hippocampal place
322 cell firing. *Hippocampus*, 1: 193–205, 1991.
- 323 **Broton-Mas JR, Schaffelhofer S, Guger C, O’Mara SM, Sanches-Vives MV.** Heterogeneous
324 spatial representation by different subpopulations of neurons in the subiculum. *Neurosci*,
325 343: 174-189, 2017.
- 326 **Brun VH, Leutgeb S, Wu H-Q, Schwarcz R, Witter MP, Moser EI, Moser M-B.** Impaired
327 spatial representation in CA1 after lesion of direct input from entorhinal cortex. *Neuron*, 57:
328 290–302, 2008.
- 329 **Burgess N.** Spatial memory: how egocentric and allocentric combine. *Trends Cog Sci*, 12: 551-
330 557, 2006.
- 331 **Burgess N, Becker S, King JA, O’Keefe J.** Memory for events and their spatial context:
332 models and experiments. *Phil Trans Royal Soc Lon. Bio Sci*, 356: 1493–1503, 2001.
- 333 **Byrne P, Becker S, Burgess N.** Remembering the past and imagining the future: A neural
334 model of spatial memory and imagery. *Psych Rev*, 114: 340–375, 2007.
- 335 **Carpenter F, Manson D, Jeffery KJ, Burgess N, Barry C.** Grid Cells Form a Global
336 Representation of Connected Environments. *Curr Biol*, 25: 1176–1182, 2015.
- 337 **Chen G, King JA, Burgess N, O’Keefe J.** How vision and movement combine in the
338 hippocampal place code. *Proc Natl Acad Sci USA*, 110: 378-383, 2013.
- 339 **Chen G, Manson D, Cacucci F, Wills TJ.** Absence of Visual Input Results in the Disruption of
340 Grid Cell Firing in the Mouse. *Curr Biol*, 26: 2335–2342, 2016.
- 341 **Cheng K.** A purely geometric module in the rat’s spatial representation. *Cognition*, 23: 149–178,

- 342 1986.
- 343 **Cho J, Sharp PE.** Head direction, place, and movement correlates for cells in the rat
344 retrosplenial cortex. *Behav Neurosci*, 115: 3-25, 2001.
- 345 **Cowen SL, Nitz DA.** Repeating firing fields of CA1 neurons shift forward in response to
346 increasing angular velocity. *J Neurosci*, 34: 232-241, 2014.
- 347 **Derdikman D, Whitlock JR, Tsao A, Fyhn M, Hafting T, Moser M-B, Moser EI.**
348 Fragmentation of grid cell maps in a multicompartiment environment. *Nat Neurosci*, 12:
349 1325–1332, 2009.
- 350 **Dudchenko PA, Zinyuk LE.** The formation of cognitive maps of adjacent environments:
351 evidence from the head direction cell system. *Behav Neurosci*, 119: 1511–1523, 2005.
- 352 **Ekstrom AD, Arnold AEGF, Iaria G.** A critical review of the allocentric spatial representation
353 and its neural underpinnings: toward a network-based perspective. *Front Hum Neurosci*,
354 <https://doi.org/10.3389/fnhum.2014.00803>, 2014
- 355 **Elmståhl S, Annerstedt L, Ahlund O.** How should a group living unit for demented elderly be
356 designed to decrease psychiatric symptoms? *Alz Dis and Assoc Disord*, 11: 47–52, 1997.
- 357 **Frank LM, Brown EN, Wilson M.** Trajectory encoding in the hippocampus and entorhinal
358 cortex. *Neuron*, 27: 169–178, 2000.
- 359 **Frank LM, Brown EN, Wilson MA.** A comparison of the firing properties of putative excitatory
360 and inhibitory neurons from CA1 and the entorhinal cortex. *J Neurophys*, 86: 2029–2040,
361 2001.
- 362 **Frank LM, Stanley GB, Brown EN.** Hippocampal plasticity across multiple days of exposure to
363 novel environments. *J Neurosci*, 24: 7681–7689, 2004.
- 364 **Fuhs MC, Vanhoads SR, Casale AE, McNaughton BL, Touretzky DS.** Influence of path
365 integration versus environmental orientation on place cell remapping between visually
366 identical environments. *J Neurophys*, 94: 2603–2616, 2005.

- 367 **Fyhn M, Hafting T, Treves A, Moser M-B, Moser EI.** Hippocampal remapping and grid
368 realignment in entorhinal cortex. *Nature*, 446: 190–194, 2007.
- 369 **Gothard KM, Skaggs WE, Moore KM, McNaughton BL.** Binding of hippocampal CA1 neural
370 activity to multiple reference frames in a landmark-based navigation task. *J Neurosci*
371 16:823–835, 1996.
- 372 **Grievies RM.** *The Neural Basis of a Cognitive Map*. University of Stirling, U.K. Retrieved from
373 <http://hdl.handle.net/1893/21878>, 2015.
- 374 **Grievies RM, Jenkins BW, Harland BC, Wood ER, Dudchenko PA.** Place field repetition and
375 spatial learning in a multicompartiment environment. *Hippocampus*, 26: 118–134, 2016.
- 376 **Hafting T, Fyhn M, Molden S, Moser M-B, Moser EI.** Microstructure of a spatial map in the
377 entorhinal cortex. *Nature*, 436: 801–806, 2005.
- 378 **Hales JB, Schlesiger MI, Leutgeb JK, Squire LR, Leutgeb S, Clark RE.** Medial entorhinal
379 cortex lesions only partially disrupt hippocampal place cells and hippocampus-dependent
380 place memory. *Cell Reprts*, 9: 893–901, 2014.
- 381 **Hardcastle K, Ganguli S, Giocomo LM.** Environmental boundaries as an error correction
382 mechanism for grid cells. *Neuron*, 86: 827–839, 2015.
- 383 **Harland B, Grievies RM, Wood ER, Dudchenko PA.** The effects of lesions to the head
384 direction cell system (lateral mammillary nuclei) on spatial cognition and place cell
385 representations. *Society for Neuroscience Abstracts*, 444.12/CC3, 2015.
- 386 **Hartley T, Burgess N, Lever C, Cacucci F, O’Keefe J.** Modelling place fields in terms of the
387 cortical inputs to the hippocampus. *Hippocampus*, 10: 369–379, 2000.
- 388 **Hayman RM, Jeffery KJ.** How heterogeneous place cell responding arises from homogeneous
389 grids-A contextual gating hypothesis. *Hippocampus*, 18: 1301–1313, 2008.
- 390 **Hermer L, Spelke ES.** A geometric process for spatial reorientation in young children. *Nature*,
391 370: 57-59, 1994.

- 392 **Hill AJ.** First occurrence of hippocampal spatial firing in a new environment. *Exp Neurol*, 62:
393 282–297, 1978.
- 394 **Hok V, Lenck-Santini P-P, Roux S, Save E, Muller RU, Poucet B.** Goal-related activity in
395 hippocampal place cells. *J Neurosci*, 27: 472-482, 2007.
- 396 **Hupbach A, Nadel L.** Reorientation in a rhombic environment: no evidence for an encapsulated
397 geometric module. *Cog Develpmnt*, 20: 279-302, 2005.
- 398 **Jankowski MM, O'Mara SM.** Dynamics of place, boundary and object encoding in rat anterior
399 claustrum. *Front Behav Neurosci*, 9: 250, 2015.
- 400 **Jankowski MM, Passecker J, Islam MN, Vann S, Erichsen JT, Aggleton JP, O'Mara SM.**
401 Evidence for spatially-responsive neurons in the rostral thalamus. *Front Behav Neurosci*, 9:
402 256, 2015.
- 403 **Jeffery KJ.** Place cells, grid cells, attractors, and remapping. *Neural Plast*, 2011, 182602, 2011.
- 404 **Julian J, Ryan J, Hamilton R, Epstein R.** The Occipital Place Area is causally involved in
405 representing environmental boundaries during navigation. *J Vision*, 15: 512, 2015.
- 406 **Julian JB, Keinath AT, Muzzio IA, Epstein RA.** Place recognition and heading retrieval are
407 mediated by dissociable cognitive systems in mice. *Proc Natl Acad Sci USA*, 112: 6503–
408 6508, 2015.
- 409 **Kennedy PJ, Shapiro ML.** Retrieving Memories via Internal Context Requires the
410 Hippocampus. *J Neurosci*, 24: 6979-6985, 2004.
- 411 **Kennedy PJ, Shapiro ML.** Motivational States Activate Distinct Hippocampal Representations
412 to Guide Goal-Directed Behaviors. *Proc Nat Acad Sci USA*, 106: 10805-10810, 2009.
- 413 **Knierim JJ, Kudrimoti HS, McNaughton BL.** Place cells, head direction cells, and the learning
414 of landmark stability. *J Neurosci*, 15: 1648–1659, 1995.
- 415 **Krupic J, Bauza M, Burton S, O'Keefe J.** Framing the grid: effect of boundaries on grid cells
416 and navigation. *J Physiol*, 594: 6489–6499, 2016.

- 417 **Krupic J, Bauza M, Burton S, Barry C, O'Keefe J.** Grid cell symmetry is shaped by
418 environmental geometry. *Nature*, 518: 232–235, 2015.
- 419 **Kubie JL, Ranck JBJr.** Sensory-behavioral correlates of individual hippocampal neurons in
420 three situations: space and context. (W. Seifert, Ed.) *Neurobiology of the Hippocampus*.
421 New York: Academic, 1983.
- 422 **Learmonth AE, Nadel L, Newcombe NS.** Children's use of landmarks: implications for
423 modularity theory. *Psych Sci*, 13: 337-341, 2002.
- 424 **Leutgeb S, Leutgeb JK, Barnes CA, Moser EI, McNaughton BL, Moser M-B.** Independent
425 codes for spatial and episodic memory in hippocampal neuronal ensembles. *Science*, 309:
426 619–623, 2005.
- 427 **Leutgeb JK, Leutgeb S, Moser M-B, Moser EI.** Pattern separation in the dentate gyrus and
428 CA3 of the hippocampus. *Science*, 315: 961–966, 2007.
- 429 **Leutgeb JK, Leutgeb S, Treves A, Meyer R, Barnes CA, McNaughton BL, Moser EI.**
430 Progressive transformation of hippocampal neuronal representations in “morphed”
431 environments. *Neuron*, 48: 345–358, 2005.
- 432 **Leutgeb JK, Leutgeb S, Treves A, Moser M-B, Moser EI.** Distinct ensemble codes in
433 hippocampal areas CA3 and CA1. *Science*, 305: 1295–1298, 2004.
- 434 **Leutgeb S, Rogozzino KE, Mizumori SJ.** Convergence of head direction and place
435 information in the CA1 region of hippocampus. *Neurosci*, 100: 11-19, 2000.
- 436 **Lever C, Burgess N, Cacucci F, Hartley T, O'Keefe J.** What can the hippocampal
437 representation of environmental geometry tell us about Hebbian learning? *Biol Cyber*, 87(5-
438 6), 356–372, 2002.
- 439 **Lever C, Burton S, Jeewajee A, O'Keefe J, Burgess N.** Boundary vector cells in the
440 subiculum of the hippocampal formation, *J. Neurosci*. 29: 9771–9777, 2009.

- 441 **Lever C, Wills T, Cacucci F, Burgess N, O'Keefe J.** Long-term plasticity in hippocampal
442 place-cell representation of environmental geometry. *Nature*, 416: 90–94, 2002.
- 443 **Markus EJ, Qin YL, Leonard B, Skaggs WE, McNaughton BL, Barnes CA.** Interactions
444 between location and task affect the spatial and directional firing of hippocampal neurons.
445 *J Neurosci*, 15: 7079-7094, 1995.
- 446 **Marozzi E, Ginzberg LL, Alenda A, Jeffery KJ.** Purely Translational Realignment in Grid Cell
447 Firing Patterns Following Nonmetric Context Change. *Cereb Cortex*, 25: 4619-4627, 2015
- 448 **Marquardt G.** Wayfinding for people with dementia: a review of the role of architectural design.
449 *HERD*, 4: 75–90, 2011.
- 450 **McNaughton BL, Battaglia FP, Jensen O, Moser EI, Moser M-B.** Path integration and the
451 neural basis of the “cognitive map.” *Nat Rev Neurosci*, 7: 663–678, 2006.
- 452 **McNaughton BL, Barnes CA, O'Keefe J.** The contributions of position, direction, and velocity
453 to single unit activity in the hippocampus of freely-moving rats. *Exp Brain Res* 52:41–49,
454 1983.
- 455 **Miao C, Cao Q, Ito HT, Yamahachi H, Witter MP, Moser M-B, Moser EI.** Hippocampal
456 Remapping after Partial Inactivation of the Medial Entorhinal Cortex, *Neuron*, 88: 590-603,
457 2015.
- 458 **Mizumori SJ.** *Hippocampal Place Fields: Relevance to Learning and Memory: Relevance to*
459 *Learning and Memory*. Oxford University Press, USA, 2008.
- 460 **Mizumori SJ, Williams JD.** Directionally selective mnemonic properties of neurons in the
461 lateral dorsal nucleus of the thalamus of rats. *J Neurosci*, 13: 4015–4028, 1993.
- 462 **Moita MAP, Rosis S, Zhou Y, LeDoux JE, Blair HT.** Putting fear in its place: remapping of
463 hippocampal place cells during fear conditioning. *J Neurosci*, 24: 7015-7023, 2004.
- 464 **Monaco JD, Abbott LF.** Modular realignment of entorhinal grid cell activity as a basis for
465 hippocampal remapping. *J Neurosci*, 31(25), 9414–9425, 2011.

- 466 **Morris RGM, Schenk F, Tweedie F, Jarrard LE.** Ibotenate Lesions of Hippocampus and/or
467 Subiculum: Dissociating Components of Allocentric Spatial Learning. *Eur J Neurosci*, 2:
468 1016–1028, 1990.
- 469 **Moser EI, Kropff E, Moser M-B.** Place cells, grid cells, and the brain's spatial representation
470 system. *Ann Rev Neurosci*, 31: 69–89, 2008.
- 471 **Muller RU, Bostock E, Taube JS, Kubie JL.** On the directional firing properties of hippocampal
472 place cells. *J Neurosci*, 14: 7235-7251, 1994.
- 473 **Muller RU, Kubie JL.** The effects of changes in the environment on the spatial firing of
474 hippocampal complex-spike cells. *J Neurosci*, 7: 1951–1968, 1987.
- 475 **Netten A.** The effect of design of residential homes in creating dependency among confused
476 elderly residents: A study of elderly demented residents and their ability to find their way
477 around homes for the elderly. *Intl J Geriatr Psychiatr*, 4: 143–153, 1989.
- 478 **Nitz DA.** Path shape impacts the extent of CA1 pattern recurrence both within and across
479 environments. *J Neurophys*, 105: 1815–1824, 2011.
- 480 **O'Keefe J.** Place units in the hippocampus of the freely moving rat. *Exp Neurol*, 51: 78–109,
481 1976.
- 482 **O'Keefe J, Burgess N.** Geometric determinants of the place fields of hippocampal neurons.
483 *Nature*, 381: 425–428, 1996.
- 484 **O'Keefe J, Conway DH.** Hippocampal place units in the freely moving rat: Why they fire where
485 they fire. *Exp Br Res*, 31: 573-590, 1978.
- 486 **O'Keefe J, Dostrovsky J.** The hippocampus as a spatial map. Preliminary evidence from unit
487 activity in the freely-moving rat. *Br Res*, 34: 171–175, 1971.
- 488 **O'Keefe J, Nadel L.** *The hippocampus as a cognitive map*. Oxford University Press, USA,
489 1978.

- 490 **O’Keefe J, Speakman A.** Single unit activity in the rat hippocampus during a spatial memory
491 task. *Exp Br Res*, 68: 1-27, 1987.
- 492 **Passini R, Pigot H, Rainville C, Tetreault M-H.** Wayfinding in a Nursing Home for Advanced
493 Dementia of the Alzheimer’s Type. *Environ Behav*, 32: 684–710, 2000.
- 494 **Pérez-Escobar JA, Kornienko O, Latuske P, Kohler L, Allen K.** Visual landmarks sharpen
495 grid cell metric and confer context specificity to neurons of the medial entorhinal cortex.
496 *eLife*, 5. <https://doi.org/10.7554/eLife.16937>, 2016.
- 497 **Peyrache A, Roux L, Schieferstein N, Buzáki G.** Transformation of head-direction signal into
498 spatial code. *bioRxiv*. <http://biorxiv.org/content/biorxiv/early/2016/09/28/075986.full.pdf>,
499 2016.
- 500 **Poucet B.** Spatial cognitive maps in animals. New hypotheses on their structure and neural
501 mechanisms. *Psych Rev*, 100: 163-182, 1993.
- 502 **Quirk GJ, Muller RU, Kubie JL, Ranck JBJr.** The positional firing properties of medial
503 entorhinal neurons: description and comparison with hippocampal place cells. *J Neurosci*,
504 12: 1945–1963, 1992.
- 505 **Rainville C, Marchand N, Passini R.** Performances of patients with a dementia of the
506 Alzheimer type in the Standardized Road-Map test of Direction Sense. *Neuropsychologia*,
507 40: 567–573, 2002.
- 508 **Rubin A, Yartsev MM, Ulanovsky N.** Encoding of head direction by hippocampal place cells in
509 bats. *J. Neurosci* 34: 1067-1080, 2014.
- 510 **Rumbarger J, Vitullo R.** *Architectural Graphic Standards for Residential Construction: The*
511 *Architect’s and Builder’s Guide to Design, Planning, and Construction Details*. John Wiley &
512 Sons, 2003.
- 513 **Savelli F, Yoganarasimha D, Knierim JJ.** Influence of boundary removal on the spatial

- 514 representations of the medial entorhinal cortex. *Hippocampus*, 18: 1270–1282, 2008.
- 515 **Schiller D, Eichenbaum H, Buffalo EA, Davachi L, Foster DJ, Leutgeb S, Raganath C.**
- 516 Memory and space: towards and understanding of the cognitive map. *J Neurosci*, 35:
- 517 13904-13911, 2015.
- 518 **Singer AC, Karlsson MP, Nathe AR, Carr MF, Frank LM.** Experience-dependent development
- 519 of coordinated hippocampal spatial activity representing the similarity of related locations. *J*
- 520 *Neurosci*, 30: 11586–11604, 2010.
- 521 **Skaggs WE, McNaughton BL.** Spatial firing properties of hippocampal CA1 populations in an
- 522 environment containing two visually identical regions. *J Neurosci*, 18: 8455–8466, 1998.
- 523 **Smith DM, Mizumori SJY.** Learning-related development of context-specific neuronal
- 524 responses to places and events: the hippocampal role in context processing. *J. Neurosci*
- 525 26: 3154-3163, 2006.
- 526 **Solstad T, Boccara CN, Kropff E, Moser M-B, Moser EI.** Representation of Geometric
- 527 Borders in the Entorhinal Cortex. *Science*, 322: 1865–1868, 2008.
- 528 **Spiers HJ, Hayman RMA, Jovalekic A, Marozzi E, Jeffery KJ.** Place field repetition and
- 529 purely local remapping in a multicompartiment environment. *Cereb Cortex*, 25: 10–25, 2015.
- 530 **Stackman RW, Golob EJ, Bassett JP, Taube JS.** Passive transport disrupts directional path
- 531 integration by rat head direction cells. *J Neurophys*, 90: 2862-2874, 2003.
- 532 **Stewart S, Jeewajee A, Wills TJ, Burgess N, Lever C.** Boundary coding in the rat subiculum.
- 533 *Phil Trans R Soc B*, 369: 20120514, 2014
- 534 **Tanila H.** Hippocampal place cells can develop distinct representations of two visually identical
- 535 environments. *Hippocampus*, 9(3), 235–246, 1999.
- 536 **Taube JS, Burton HL.** Head direction cell activity monitored in a novel environment and during
- 537 a cue conflict situation. *J Neurophys*, 74: 1953–1971, 1995.
- 538 **Taube JS, Muller RU, Ranck JBJr.** Head-direction cells recorded from the postsubiculum in

- 539 freely moving rats. I. Description and quantitative analysis. *J Neurosci*, 10: 420–435, 1990a.
- 540 **Taube JS, Muller RU, Ranck JBJr.** Head-direction cells recorded from the postsubiculum in
541 freely moving rats. II. Effects of environmental manipulations. *J Neurosci*, 10: 436–447,
542 1990b.
- 543 **Taube JS, Wang SS, Kim SY, Frohardt RJ.** Updating of the spatial reference frame of head
544 direction cells in response to locomotion in the vertical plane. *J Neurophys*, 109: 873-888,
545 2013.
- 546 **van der Voordt DJ.** [Losing your way in the nursing home: spatial orientation from an
547 architectural viewpoint. A review]. *Tijdschrift Voor Gerontologie En Geriatrie*, 24: 220–227,
548 1993.
- 549 **Whitlock JR, Derdikman D.** Head direction maps remain stable despite grid map
550 fragmentation. *Front Neural Circ*, 6: 9, 2012.
- 551 **Wilson MA, McNaughton BL.** Dynamics of the hippocampal ensemble code for space.
552 *Science*, 261: 1055–1058, 1993.
- 553 **Winter, SS, Clark BJ, Taube JS.** Disruption of the head direction cell network impairs the
554 parahippocampal grid cell signal. *Science* 347: 870-874. 2015.
- 555 **Wood ER, Dudchenko PA, Robitsek RJ, Eichenbaum H.** Hippocampal neurons encode
556 information about different types of memory episodes occurring in the same location.
557 *Neuron*, 27: 623-633, 2000.
- 558 **Zhang S, Schönfeld F, Wiskott L, Manahan-Vaughan D.** Spatial representations of place
559 cells in darkness are supported by path integration and border information. *Front Behav*
560 *Neurosci*, 8: 222, 2014.
- 561 **Zhang S-J, Ye J, Miao C, Tsao A, Cerniasukas I, Ledergerber D, Moser M-B, Moser EI.**
562 Optogenetic dissection of entorhinal-hippocampal functional connectivity. *Science* 340:

563 273, 2013.

564 **Zinyuk L, Kubik S, Kaminsky Yu, Fenton AA, Bures J.** Understanding hippocampal activity
565 using purposeful behavior: place navigation induces place cell discharge in both task-
566 relevant and task-irrelevant spatial reference frames. Proc Nat Acad Sci USA, 97: 3771-
567 3776, 2000.

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572 **Figure Legends**

573

574 **Figure 1** Spatially modulated cell types in the mammalian brain. **Top left:** The firing rate map of
575 a dCA1 (hippocampus) place cell. Action potentials and dwell time are binned, smoothed and
576 divided to give a spatial map of the cell's firing rate. Generally, hot colours represent high firing
577 rates, cold colours represent low firing rates, and white represents unvisited locations. This cell
578 has an area of high firing located to the Northeast of the environment, and this area is known as
579 this cell's 'place field'. **Top middle:** An example of a medial entorhinal cortex (mEC) head
580 direction cell. These 'polar' plots show the action potentials of the cell, binned in terms of the
581 animal's head direction at the time and divided by the amount of time spent facing that direction
582 overall. This cell fires at a high rate when the animal is facing to the North (90°) within the
583 environment, and this is referred to as the cell's preferred firing direction. **Top right:** The firing
584 rate map of an mEC grid cell. This is produced using the same method as for the place cell.
585 Multiple firing fields can be observed which form a triangular or hexagonal grid that spans the
586 environment. **Middle:** Firing rate maps of a single subicular boundary cell recorded in three
587 different environments, a circle, a diamond, and a square, placed in the same room. Note that

588 the cell continues to fire along walls that subtend the rat at the same angle (North-easterly
589 boundaries) even when the environment changes (adapted from Lever et al., 2009; Figure 3,
590 cell 2d). **Bottom left:** The firing rate map of a border cell recorded in the mEC. **Bottom right:**
591 An example of a modelled boundary vector cell, generated in the same way as in Hartley et al.
592 (2000).

593
594 **Figure 2** Examples of local encoding by place cells. Firing rate maps utilise the colour axis
595 given below **B**. **A**, an example dCA1 place cell recorded in the maze used by Skaggs and
596 McNaughton (1998). **B**, dCA1 place field repetition in the four compartment apparatus used by
597 Spiers et al. (2015). **C**, Derdikman et al.'s (2009) hairpin maze. An example of mEC grid field
598 repetition is shown in the top row of firing rate maps, recorded when the animal moved through
599 the maze from left to right (left map) and right to left (right map). A similar example of dCA1
600 place field repetition is shown in the rate maps below these. **D**, Two example dCA1 place cells
601 recorded by Lever et al. (2002) in a circular and square environment of the same size.

602
603 **Figure 3** Place field repetition depends on direction. In the top rows, the maze schematics are
604 shown, and in the bottom rows examples of the corresponding firing activity maps are provided.
605 The colour bar next to **A** corresponds to **C** also. **A**, The maze used by Fuhs et al. (2005); left:
606 example of dCA1 place field repetition when compartments were parallel and connected by a
607 corridor (corridor data are ignored); right: the same cell showed a lack of repetition when the
608 compartments were rotated 90°, and abutted each other. **B**, The mazes used by Nitz et al.
609 (2011) and Cowen and Nitz (2014). Rats ran along a spiral path of either a square (left) or
610 circular (right) maze. In both, linearised rate maps revealed that dCA1 place cells have multiple
611 fields which occur when the animal is facing the same direction. **C**, The mazes used by Grieves
612 et al. (2016). Two example dCA1 place cells are shown, one per row. Left column: place field

613 repetition when animals navigate four parallel compartments connected by a corridor; right
614 column: absence of place field repetition when the same compartments are arranged in a radial
615 formation.

616

617 **Figure 4** Mixed evidence for pattern repetition changes with learning. **A**, Top diagram shows a
618 floor plan of the maze used by Carpenter et al. (2015). The second row shows representative
619 rate maps from one mEC grid cell for the two compartments in an early session (session 4)
620 where it fires similarly in two compartments. The third row shows maps for the same cell in a
621 later session (session 19). Here it fires with a global representation - the grid pattern extends
622 between the environments as if the wall between them was not present. The bottom scatter plot
623 shows the result of subtracting the measure of local encoding from one of global encoding for all
624 grid cells that were recorded at differing session intervals of exposure. As animals were
625 exposed for more sessions their representation became more global, and thus the line
626 corresponds to a linear increase. **B**, Top diagram shows a floor plan of the maze used by Singer
627 et al. (2010). The second row shows the firing rate map of a dCA1 place cell which shows
628 pattern repetition, and the row below this shows the same data when the color map is capped at
629 3Hz. The bottom bar graph shows the normalised overlap or similarity of place cell firing (when
630 linearised) for cells recorded by Singer et al. (2010) in their multi-arm maze. Greater overlap
631 here is suggestive of pattern repetition in the maze arms and this seems to increase with
632 training. **C**, The top diagram shows a schematic of the maze used by Grieves et al. (2016). The
633 plot below this shows the average level of correlation between compartments as a function of
634 recording session. Correlations between compartments in the parallel version of the task were
635 consistently higher than those in the radial version. Moreover, the level of correlation in either
636 configuration did not change significantly over the course of the experiment. **D**, Top diagram
637 shows a mock firing rate map for a cell recorded in the maze used by Spiers et al. (2015). The

638 numbers show the distance of each compartment (in compartments) from the one with the
639 highest firing rate. The plot below this shows the highest compartment firing rate (compartment
640 0) and firing rates of every other compartment ranked in order of their distance from this
641 (compartments 1-3) found by Spiers et al. (2015). This relationship is shown for the first day of
642 recording and the last. Because this analysis selects the highest firing rates for compartment 0,
643 this value is significantly higher. If some form of rate coding or remapping was present the other
644 compartment distances would also be distinguishable in terms of firing rate. However, this is not
645 the case and this effect does not develop with training.

646

647 **Figure 5** Pattern repetition likely reflects environmental geometry. The color bar below **A**
648 applies to **A**, **B** and **D**, and the color bar below **C** applies to **C** and **E**. **A**, Example adapted from
649 O'Keefe and Burgess (1996) of a dCA1 place cell recorded in an environment where the walls
650 could be moved to change its size. In the small square the cell has a field in the top left corner.
651 When the square's length was extended (bottom left plot) the cell's firing remains unchanged.
652 However, when the square's width was extended (top right plot) the place cell's field extended
653 proportionally. When the environment was extended isometrically the cell's field faintly extends
654 equally in all directions (bottom right plot). These results show that place cell firing is at least
655 partly dictated by boundaries in the animal's environment and that some boundaries exert more
656 control over a given cell than others. **B**, Middle plot shows the firing rate map of a dCA1 place
657 cell recorded in a square environment with a bisecting wall. Note that the cell has two fields, one
658 on each side of the barrier. The plot below this is of a modelled place cell generated using BVC
659 inputs and shows the same pattern of firing (figure adapted from Barry and Burgess 2007). **C**,
660 The firing rate maps of an example, modelled, boundary vector cell in four different shaped
661 environments. This cell maintains the same preferred firing direction (roughly North West) and
662 distance in all environments (modelled using the Boundary Vector Cell model, Barry et al.

663 2006). Note that in the top right plot, where a barrier bisects the environment the BVC's firing is
664 also bisected and takes on a repetitive appearance. **D**, Example boundary cell recorded from
665 the rat subiculum in a three platform environment, adapted from Stewart et al. 2014. The cell
666 fires along the West boundary of each platform, which in this case is a vertical drop. **E**, A dCA1
667 place cell recorded in an elevated platform maze composed of four parallel alleyways. In this
668 maze we can see that vertical drops are also sufficient to drive pattern repetition in place cells
669 (Grieves 2015). This cell does not fire in the far right arm of the maze, and this is consistent with
670 the findings of Spiers et al. (2015) and Grieves et al. (2016) which suggest that place field
671 repetition is a continuous phenomenon. In repetitive environments, many place cells exhibit
672 repeating fields in every sub-compartment, but some only exhibit them in a minority of
673 compartments and some do not exhibit repeating fields at all. This suggests that the strength of
674 different inputs (e.g., geometry, self-motion) may vary for different place cells.

675

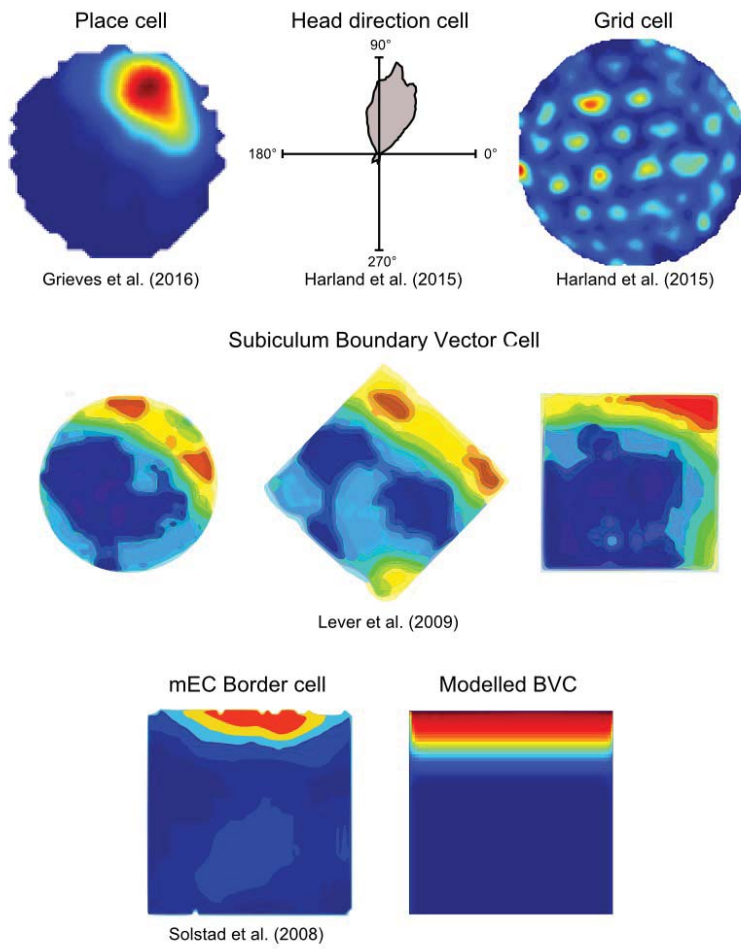


Figure 1

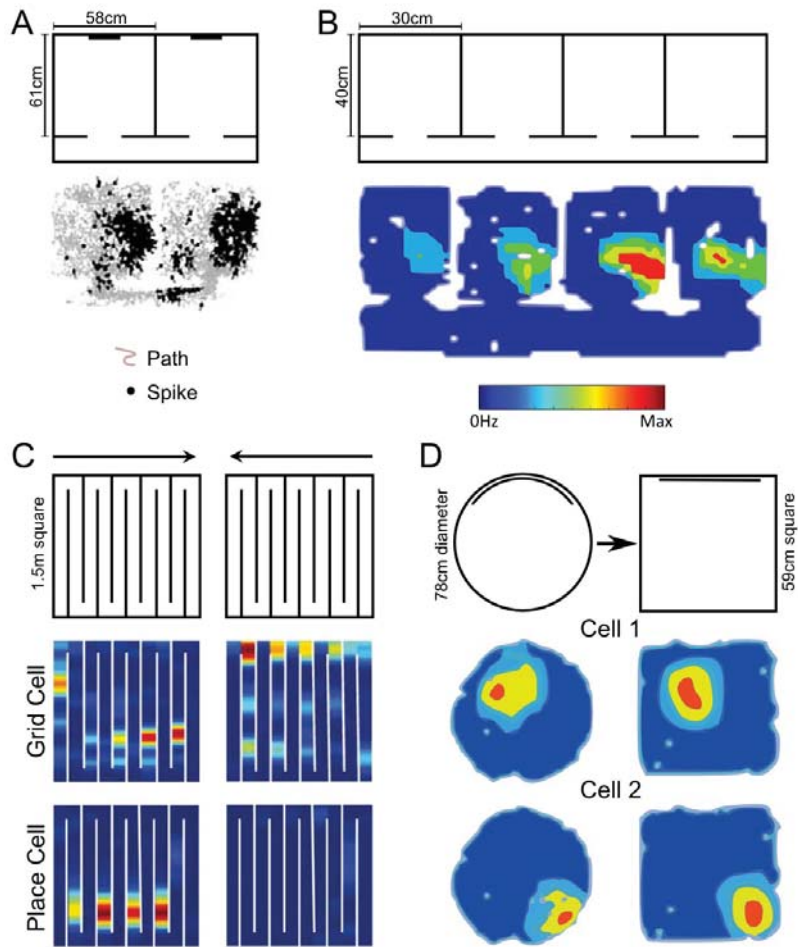


Figure 2

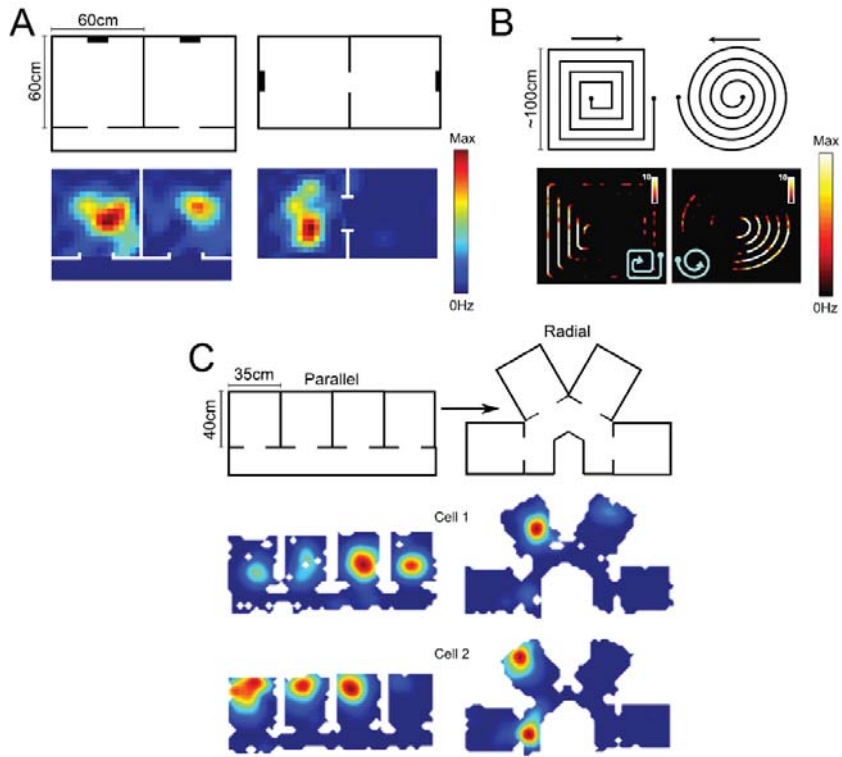


Figure 3

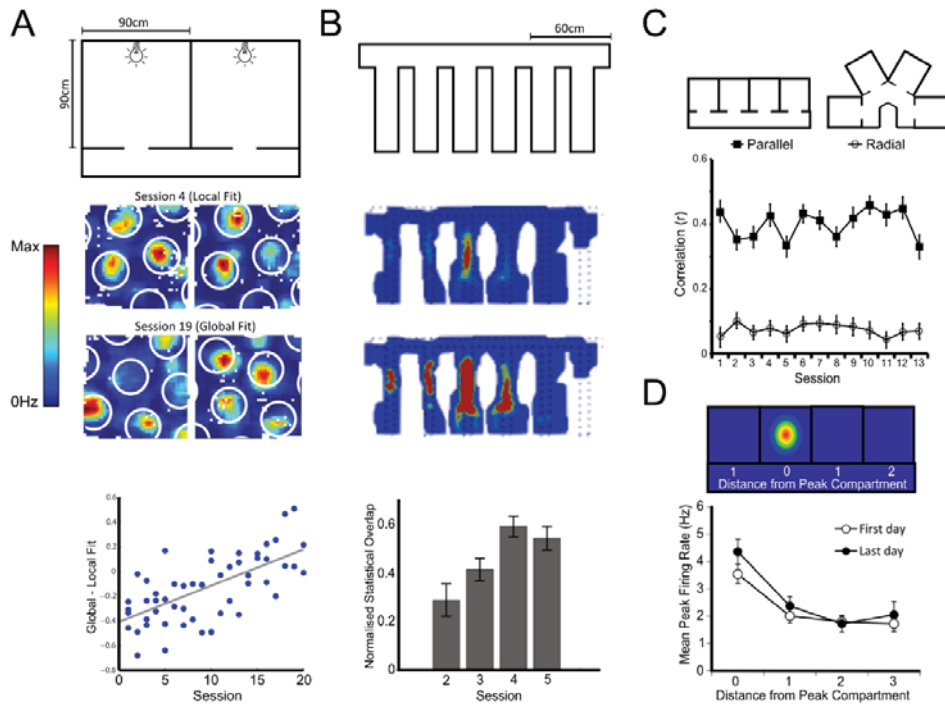


Figure 4

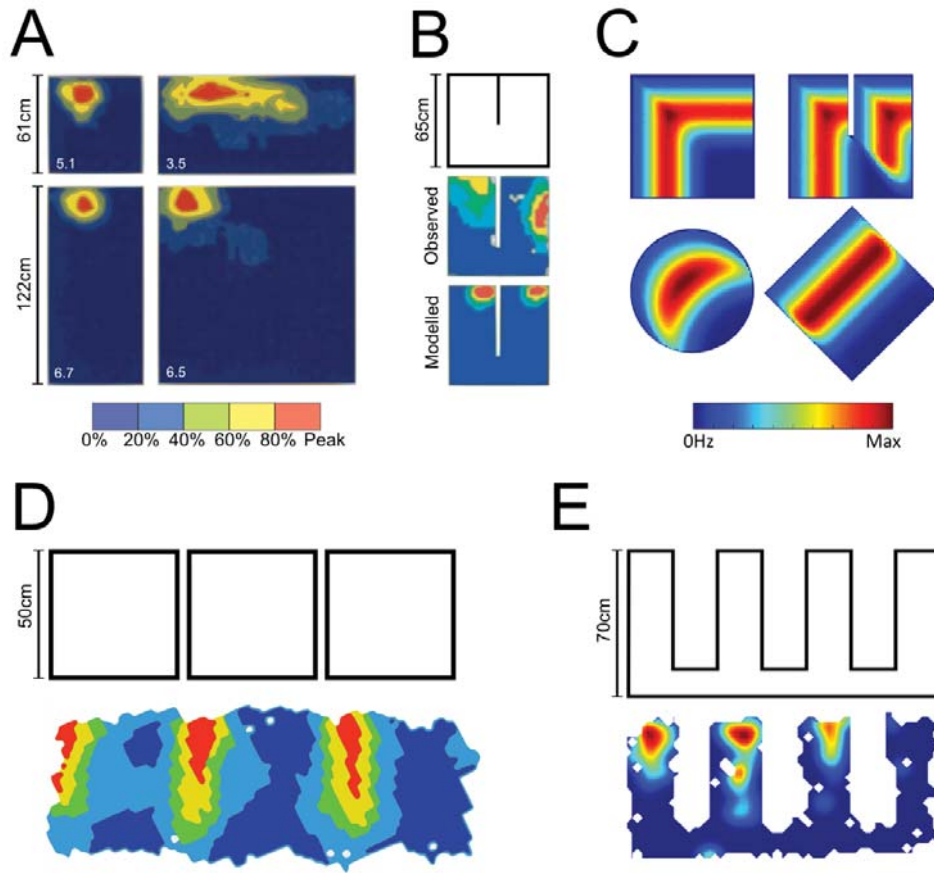


Figure 5