

1 The place-cell representation of volumetric 2 space in rats

3 Roddy M. Grieves^{1*}, Selim Jedidi-Ayoub¹, Karyna Mishchanchuk¹, Anyi Liu¹,
4 Sophie Renaudineau¹ and Kate J. Jeffery^{1*}

5 ¹University College London, Institute of Behavioral Neuroscience, Department of
6 Experimental Psychology, London, United Kingdom

7
8 *For correspondence:
9 r.grieves@ucl.ac.uk (RMG)
10 k.jeffery@ucl.ac.uk (KJJ)

11

12

13 Abstract

14 Place cells are spatially modulated neurons found in the hippocampus that underlie
15 spatial memory and navigation: how these neurons represent 3D space is largely unknown.
16 We wirelessly recorded place cells in rats as they explored a cubic lattice climbing frame
17 which could be aligned or tilted with respect to gravity. Place cells represented the entire
18 volume of the mazes: the activity of these cells tended to be aligned with the maze axes, and
19 when it was more difficult for the animals to move vertically the cells represented space less
20 accurately and less stably. These results demonstrate that surface dwelling animals also
21 represent 3D space and suggests there is a fundamental relationship between environment
22 structure, gravity, movement and spatial memory.

23 **Introduction**

24 Place cells are neurons in the hippocampus that fire when an animal visits specific
25 regions of its environment, called place fields, and are thought to provide the foundation for
26 an internal representation of space, or ‘cognitive map’ (1, 2). The question arises as to
27 whether this map is three-dimensional, and if so whether the properties are the same in all
28 dimensions (3–5). This is important not just for spatial mapping *per se* but also because the
29 spatial map may form the framework for other types of cognition in which information
30 dimensionality is higher than in real space. Understanding how the brain integrates
31 information across dimensions is thus of theoretical importance.

32 A longstanding question concerns whether this map represents three-dimensional
33 space or whether it is essentially flat, with reduced information about the vertical dimension.
34 A previous study of place cells in rats (6) found vertical elongation of the place fields when
35 rats climbed either a pegboard wall studded with footholds or a spiral track, suggesting that
36 perhaps the cognitive map has a lower resolution for vertical space than for horizontal space
37 (i.e., is anisotropic). This finding was supported by observations that entorhinal grid cells,
38 thought to provide a spatial metric for place cells, showed absent spatial processing in the
39 vertical dimension. However, in a more recent experiment, when rats climbed a wall covered
40 with chicken wire place cells were found to have normally shaped firing fields, although fields
41 themselves occurred with lower probability than on the floor (7). This meant that although the
42 firing of spatial neurons differed between the floor and the wall, the horizontal and vertical
43 components of firing on the wall did not appreciably differ. Taking these findings together, it
44 seems that the differences in spatial encoding previously seen in the vertical dimension may
45 be due to the different constraints on movement, or the locomotor ‘affordances’ in the
46 different dimensions (8). Meanwhile, a study of flying bats found that place fields did not
47 deviate statistically from spherical (9), suggesting a spatial map of equal resolution in all
48 dimensions (isotropic).

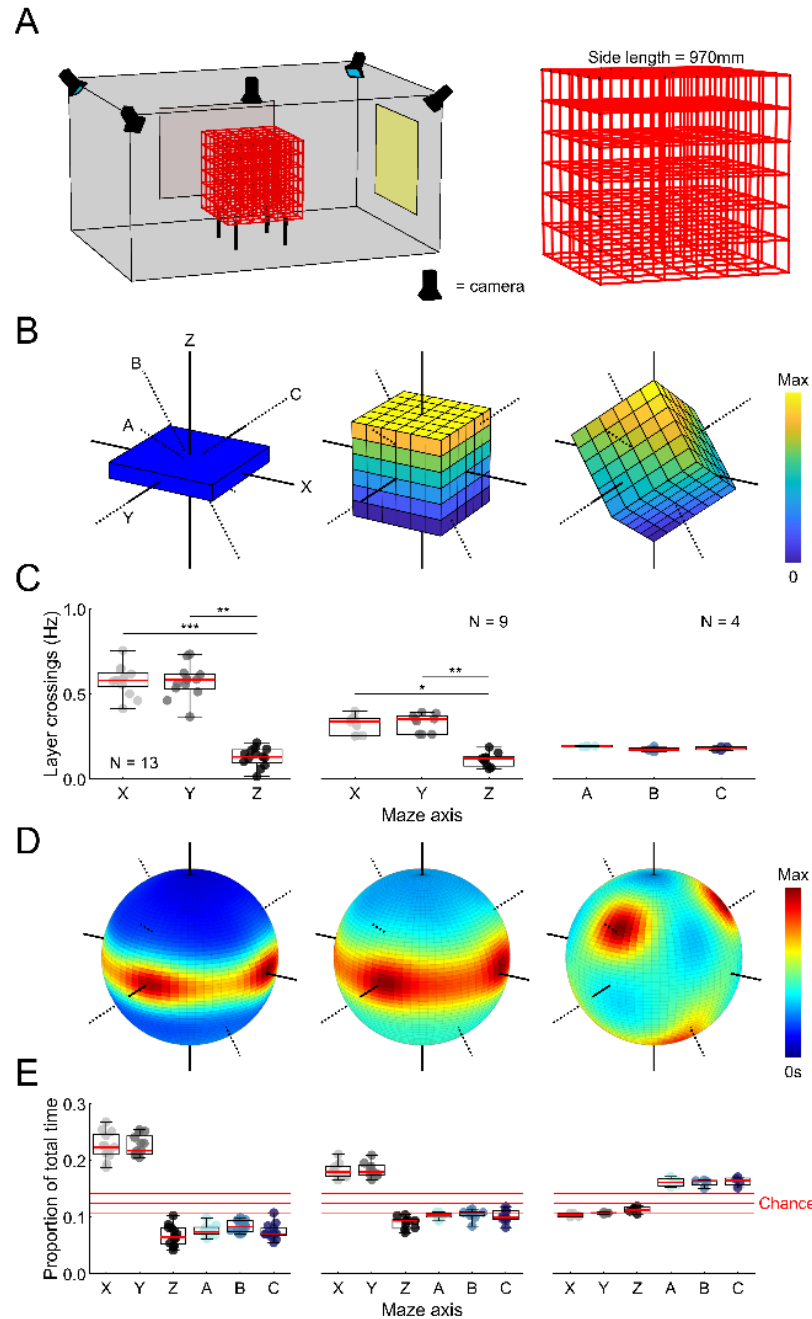
49 The difference from the rat findings could be due either to the ecological requirements of
50 the species and their differential need for a volumetric map. Alternatively, it could be
51 because the environmental affordance for flight is similar in horizontal vs. vertical dimensions
52 whereas for surface travel the affordances in different dimensions differ. The present
53 experiment aimed to untangle these issues by exploring, in rats, the interaction between
54 gravity, which is what distinguishes horizontal from vertical, and the locomotor affordances of
55 the environment. Animals were recorded using digital telemetry as they explored a
56 volumetric space – an open cubic lattice – through which they could move freely and which
57 had equal properties in all three spatial dimensions. Place cells exhibited firing fields
58 throughout this volume, confirming that these cells underlie a fully three-dimensional
59 volumetric representation of space. Furthermore, we found that place fields tended to be
60 elongated along the axes of the maze (the directions aligned with the boundaries, and in
61 which travel was easiest) with greater elongation for the vertical axis and a resultant lower
62 spatial information and decoding accuracy. We then tilted the lattice so that the three planes
63 of movement all had the same relationship to gravity, and were thus all equally easy (or
64 hard) to traverse. We found that the elongation of the axes followed the tilt of the maze, and
65 the difference between horizontal and vertical place field metrics disappeared. Thus, it
66 seems that differences between horizontal and vertical metrics in spatial encoding arise from
67 the greater movement constraints (lower locomotor affordance, resulting in and greater effort
68 and lower movement time in that dimension) for vertical than horizontal travel, rather than
69 from an intrinsic difference in resolution between directions aligned with vs. orthogonal to
70 gravity. These findings suggest that locomotor affordances in the environment, of which
71 gravity is one modulator, have an effect on encoding structure and accuracy of the spatial
72 map. This may have implications for spatial mapping not just in vertical space, but in any
73 space in which locomotion is difficult or interrupted.

74

75 **Results**

76 *Rats explored the lattice maze fully, but adopted a layer strategy*

77 Rats explored the lattice mazes (Fig. S1) fully, with slightly more coverage in the
78 aligned than the tilted configuration (Fig. S2A-B). In both configurations they spent more time
79 in the lower half, and remained closer to the maze boundaries (Fig. S2C-D). We looked for
80 horizontal movement bias (10) by counting transitions between maze units. In the aligned
81 configuration animals explored the three dimensions differently (median layer transitions/s
82 along X,Y & Z: 0.34, 0.35 & 0.12 Hz, $\chi^2(2) = 14.0$, $p = .0009$, $\eta_p^2 = 0.51$, FT) and post-hoc
83 tests confirmed that they made significantly fewer layer crossings along the (vertical) Z-
84 dimension (X vs Z & Y vs Z, $p < .02$, X vs Y, $p > .99$, Fig. 1A-C). Animals also moved
85 significantly more slowly along the Z-axis of the aligned lattice (Fig. S2E). By contrast,
86 animals moved equivalently along the (now rotated) axes of the tilted lattice, which we
87 labelled A, B and C (Fig. 1C & Fig. S2A).



88

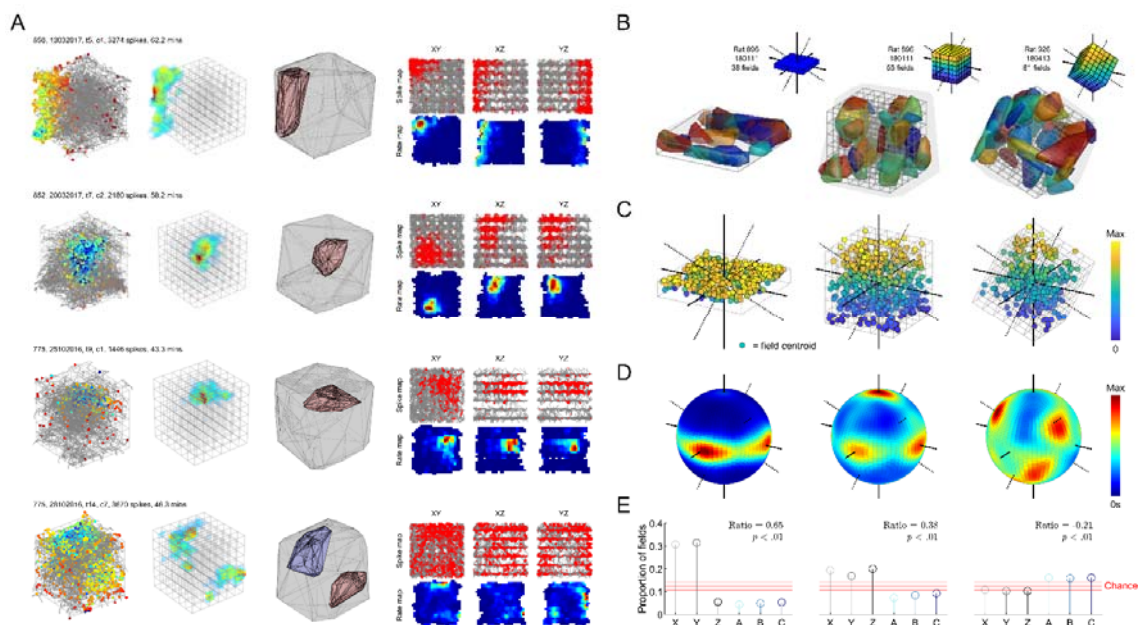
89 **Figure 1:** Behavior of animals in the lattice maze. (A) Room and maze (shown in aligned
 90 configuration). (B) Schematic of the maze configurations, color-coded to show height. (C) Frequency
 91 with which animals crossed between lattice layers in the two configurations. Each marker represents
 92 an animal. Note preference for horizontal crossings in the aligned lattice maze. (D) Three-dimensional
 93 heat plots of trajectory distribution for the three maze configurations, ordered as in (B) and (C). Note
 94 concentration around horizontal trajectories for the arena and aligned maze, and along the three axes
 95 for the tilted maze. (E) Each marker represents an animal: graphs show proportion of total session
 96 time spent moving roughly parallel to each possible maze axis. Red lines show the 1st 50th and 99th
 97 percentile of a shuffle distribution (see Methods).

98 In the arena, animals' movements were mostly parallel to the horizontal X and Y-
99 axes (median proportion of time along X & Y: 0.22 & 0.22) and their movements were
100 distributed between these two axes equally ($\chi^2(1) = 0.08$, $p = .78$, $\eta_p^2 = 0.001$, FT). In the
101 aligned lattice animals spent more time moving parallel to the X and Y axes than would be
102 expected by chance, but they rarely moved along the other axes (Z, or A, B and C; median
103 proportion of time along A, B, C, X, Y & Z respectively: 0.10, 0.11, 0.10, 0.18, 0.18 & 0.09,
104 chance 97.5th percentile: 0.13). Animals thus travelled along the maze axes significantly
105 differently ($\chi^2(2) = 14.0$, $p = .0009$, $\eta_p^2 = 0.52$, FT) and post-hoc tests confirmed that they
106 explored the X and Y axes similarly, but the Z axis significantly less (X vs Z & Y vs Z, $p <$
107 $.02$, X vs Y, $p > .99$). This again confirms a strong horizontal bias in their movements when
108 climbing through the lattice (10). Lastly, in the tilted lattice only the A, B and C axes of this
109 maze were traversed more than chance (median proportion of time along A, B, C, X, Y & Z:
110 0.16, 0.16, 0.16, 0.10, 0.11, 0.11, chance 97.5th percentile: 0.13) and these axes were
111 traversed equally ($\chi^2(2) = 1.5$, $p = .47$, $\eta_p^2 = 0.13$, FT). These effects can be seen in Fig. 1D-
112 E.

113 *Place fields were distributed uniformly throughout the lattices*

114 In total we recorded 756 place cells in the lattice maze environments from 13 rats
115 (Table S2). Representative place cells can be seen in Fig. 2A and Fig. S3. The proportion of
116 active cells (having at least one place field) in the 3D lattice did not differ significantly from in
117 the 2D arena (arena & aligned lattice: 82.5% & 85.2%, $\chi^2(1) = 1.51$, $p = .28$, OR = 0.82;
118 arena & tilted lattice: 82.5% & 83.8%, $\chi^2(1) = 0.18$, $p = .67$, OR = 0.91, Chi-square tests of
119 equal proportions). However, the number of place fields per cell differed between mazes
120 (arena, aligned and tilted median fields/cell: 1.0, 1.0 & 2.0; $\chi^2(2) = 48.63$, $p < .0001$, $\eta_p^2 =$
121 $.04$, K-W) with cells unsurprisingly exhibiting significantly more fields in the lattice (arena vs
122 aligned & arena vs tilted, $p < .0001$, aligned vs tilted, $p = .29$, Fig. S4A-B). However fields
123 were also more sparse in the lattice [median of 2.21 fields per m³ in the open field but only

124 0.69 per m³ in the aligned configuration and 1.23 per m³ in the tilted configuration ($\chi^2(2) =$
 125 781.7, $p < .0001$, $\eta_p^2 = .70$, K-W; arena vs aligned & arena vs tilted, $p < .0001$, aligned vs
 126 tilted, $p = .001$, Fig. S4C]. Fields were distributed throughout the lattices uniformly [Fig. 2B-
 127 C, GP algorithm (see supplementary methods) aligned observed slope: 2.68, shuffle 95%
 128 confidence intervals: 2.65 & 2.79; tilted observed slope: 2.63, shuffle 95% confidence
 129 intervals: 2.61 & 2.84] and in each case the median field centroids lay close to the maze
 130 center (Fig. S4F).



131

132 **Figure 2:** Distribution of place fields in the lattice maze. (A) Representative example place cells and
 133 their activity in the aligned lattice maze. Four cells are shown, one per row. First column shows the
 134 path of the animal and spikes plotted as colored markers. Marker color denotes spike density. Second
 135 column shows the three-dimensional firing rate map. Colors denote firing rate and follow the color axis
 136 of (D) but areas of low or no firing are transparent. Third column shows the convex hull of the dwell
 137 time map as a grey outline and the convex hull of any detected place field(s) as separate (color-
 138 coded) polygons. Last column shows the spike and firing rate maps when the data are projected onto
 139 the three possible cardinal planes. (B) Representative arena, aligned and tilted lattice recording
 140 sessions demonstrating homogenous distribution of fields. To allow clearer distinction of separate
 141 (color-coded) fields, only fields with a volume less than 300 voxels (one voxel = 50mm³) are shown
 142 (~2/3 total). (C) Location of place field centroids. Colors denote vertical position. (D) Three-
 143 dimensional heat plots of place field orientation for the three maze configurations, ordered as in (B)
 144 and (C). Note concentration around horizontal axes for the arena and along the three axes of the
 145 aligned and tilted mazes. (E) Graphs show proportion of total fields oriented roughly parallel to each
 146 possible maze axis. Red lines show the 1st 50th and 99th percentile of a shuffle distribution. The
 147 normalized ratio of XYZ to ABC oriented fields is given as well as the probability of observing this
 148 value by chance (see Methods).

149 *Place fields were elongated in all dimensions*

150 Place fields were larger in the two lattice mazes (arena, aligned & tilted median
151 volume: 1065, 1332 & 1535 cm³, $\chi^2(2) = 63.12$, $p < .0001$, $\eta_p^2 = .04$, K-W; arena vs aligned &
152 arena vs tilted, $p < .0001$) and slightly larger in the tilted than aligned lattice (aligned vs tilted,
153 $p = .021$; Fig. S4D). However, place field diameter varied very little between mazes with only
154 a small, albeit significant, difference between the arena and tilted lattice (arena, aligned &
155 tilted enclosing diameter: 0.65, 0.67 & 0.68m, $\chi^2(2) = 7.3$, $p = .0255$, $\eta_p^2 = .004$, K-W; arena
156 vs aligned & aligned vs tilted, $p > .35$, arena vs tilted, $p = .020$, Fig S4E). Place fields in all
157 conditions were slightly elongated, with elongation indices (see supplementary methods) that
158 deviated significantly from 1 (arena median elongation: 1.65, $Z = 22.81$, $p < .0001$, $U3 = 0$;
159 aligned median elongation: 1.86, $Z = 21.29$, $p < .0001$, $U3 = 0$; tilted median elongation:
160 1.86, $Z = 17.29$, $p < .0001$, $U3 = 0$, WSR, Fig. S5A-B). It is unlikely these effects were due to
161 inhomogeneous sampling (Fig. S9). Field heights were bimodal in the aligned lattice,
162 suggesting that vertically elongated fields were longer than horizontally elongated ones (Fig.
163 S5D-E). Place field elongation in the lattice mazes was weakly but significantly positively
164 correlated with field centroid distance from maze center (Fig. S5F).

165 In the square arena place fields were inhomogeneously distributed ($\chi^2(5) = 918.1$,
166 $p < .0001$, Chi-square test of expected proportions, Fig. 2D) and its axis ratio (total XYZ
167 fields - total ABC fields / sum of these) was significantly greater than zero (observed ratio:
168 0.65, shuffle 1st & 99th percentile ranks: -0.07 & 0.01) indicating that significantly more fields
169 were oriented parallel to the XYZ axes than ABC axes. Closer inspection revealed that only
170 the horizontal X and Y-axes were represented at an above chance level (X & Y: 31 & 32% of
171 fields, chance 99th percentile: 12.5%, Fig. 2E) and that the fields aligned with these axes
172 were of a similar length ($\chi^2(1) = 0.01$, $p = .97$, $\eta_p^2 < .0001$, K-W).

173 In the aligned lattice fields were also inhomogeneously distributed ($\chi^2(5) = 152.2$, $p <$
174 $.0001$, Chi-square test of expected proportions, Fig. 2D) and its axis ratio was again

175 significantly greater than zero (observed ratio: 0.39, shuffle 1st & 99th percentiles: -0.072 & -
176 0.001). In this maze only the X, Y and Z-axes were represented at an above chance level (X,
177 Y & Z: 19, 17 & 20% of fields, chance 99th percentile: 12.5%, Fig. 2E) and to an equal
178 degree ($\chi^2(2) = 5.0, p = .08$, Chi-square test of expected proportions). However, the fields
179 aligned with these axes differed in length (median length, X, Y & Z: 64.3, 57.9 & 78.2 cm,
180 $\chi^2(2) = 26.8, p < .0001, \eta_p^2 = .079$, K-W) and post-hoc tests confirmed that fields aligned with
181 the Z-axis were significantly longer (X vs Z & Y vs Z, $p < .009$, X vs Y, $p = .074$).

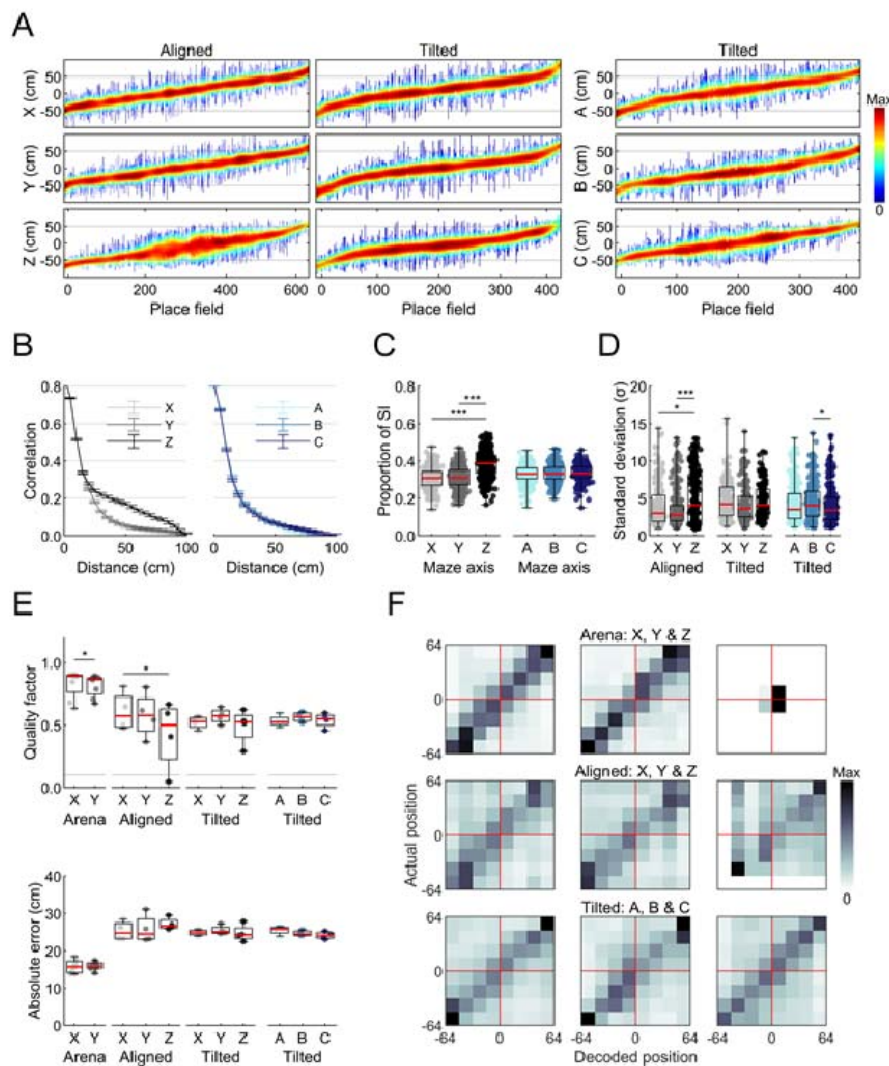
182 Lastly, fields in the tilted lattice took on a different non-random distribution ($\chi^2(5) =$
183 27.7, $p < .0001$, Chi-square test of expected proportions, Fig. 2D) with an axis ratio
184 significantly less than zero (observed ratio: -0.21, shuffle 1st & 99th percentiles: -0.072 &
185 -0.001) indicating that significantly more fields were oriented parallel to the ABC axes than
186 XYZ axes. In line with this only the A, B and C-axes were represented at an above-chance
187 level (A, B & C: each 16% of fields, chance 99th percentile: 12.5%, Fig. 2E) and these fields
188 were all of a similar length ($\chi^2(2) = 0.18, p = .91, \eta_p^2 < .0001$, K-W). For all three mazes an
189 independent approach also confirmed that field elongation was best described as parallel to
190 each maze's axes (see supplementary results, Fig. S6).

191 *Spatial coding was less accurate along the vertical dimension*

192 If fields were larger along a specific dimension, firing rate maps would be more highly
193 autocorrelated in this dimension (Fig. S8A-B). In the aligned lattice, autocorrelation values
194 indeed differed between the three axes ($F(2, 26896) = 676.7, p < .0001, \eta_p^2 = 0.048$) with a
195 significant interaction between distance and axis ($F(40, 26896) = 18.8, p < .0001, \eta_p^2 =$
196 0.027) due to higher correlations in the Z-axis (X, Y & Z, mean correlation: 0.165, 0.171 &
197 0.228; X vs Z and Y vs Z, $p < .0001$, X vs Y, $p = .018$). In the tilted lattice correlation values
198 differed between the A, B and C axes ($F(2,17000) = 22.7, p < .0001, \eta_p^2 = 0.003$) with an
199 interaction between distance and axis ($F(40,17000) = 2.23, p < .0001, \eta_p^2 = 0.005$) although

200 these relationships are associated with small effect sizes. In contrast to the aligned lattice no
201 one axis was associated with higher correlations than the others: instead, the A-axis was
202 associated with slightly smaller correlations (A, B & C, mean correlation: 0.149, 0.161 &
203 0.160; A vs B and A vs C, $p < .0001$, B vs C, $p > .99$, pairwise comparisons with Bonferroni
204 correction). These effects can be seen in Fig. 3B. Similar effects were obtained using the
205 median overall central component of autocorrelograms (Fig. S8C) and using an independent
206 approach to assess the binary morphological connectivity of lattice firing rate maps (Fig.
207 S8D). Down-sampling trajectory data to account for the horizontal bias in animals'
208 movements confirmed that this bias does not account for these effects (Fig. S9).

209 To explore this reduced encoding resolution effect further we also looked at the
210 spatial information content along each ratemap axis by calculating the spatial information
211 content after projecting maps onto the Cartesian planes. If fields were larger or if firing was
212 more diffuse along one dimension, place fields would appear larger in slices along the
213 orthogonal axes, resulting in a lower spatial information score (see Fig. S8A-B for an
214 example). The spatial information exhibited by place cells in the aligned lattice did differ
215 along the three axes (median proportion of total spatial information in X, Y & Z slices: 0.308,
216 0.310, 0.387, $\chi^2(2) = 153.3$, $p < .0001$, $\eta_p^2 = .119$, FT) with horizontal slices along the Z-axis
217 demonstrating the greatest spatial information (X vs Z & Y vs Z, $p < .0001$, X vs Y, $p > .99$).
218 This was not the case in the tilted lattice (median proportion of total spatial information in A,
219 B & C slices: 0.332, 0.333, 0.335, $\chi^2(2) = 1.4$, $p = .498$, $\eta_p^2 = .001$, FT). These effects can be
220 seen in Fig. 3C. Equivalent effects were also observed when using mutual information (data
221 not shown). As before, down-sampling ruled out horizontal movement bias as an explanation
222 for these effects (Fig. S9).



223

224 **Figure 3:** Spatial information in three dimensions. (A) The span and normalized activity of every
 225 recorded place field in the lattice mazes. Vertical lines represent place fields, ordered along the x-axis
 226 by their position relative to the lattice central node. Line color represents normalized firing rate. (B)
 227 The mean and SEM autocorrelation found for all place cells in the aligned lattice (left) and tilted lattice
 228 (right) at increasing distances or spatial lag. Correlations at low distances are high along all axes,
 229 however, correlations at longer distances remain higher for longer along the Z axis of the aligned
 230 lattice. (C) For every cell we generated three 2-dimensional maps by taking the mean along each axis
 231 of the 3-dimensional firing rate map. Next we calculated the spatial information content of each map
 232 and shown here is the proportion of total spatial information found per projection for the aligned lattice
 233 (left) and tilted lattice (right). In the aligned lattice spatial information content is significantly higher
 234 when data are projected onto an X, Y plane, suggesting that place cell firing is more precise in these
 235 axes. (D) The standard deviation of orthogonal 1-dimensional Gaussians fitted to place fields in each
 236 lattice maze. (E) We decoded the position of animals in each environment through Bayesian methods
 237 using the activity of place cells. Top: the quality factor (decoding accuracy relative to chance) of
 238 decoded trajectories in each axis. A quality of 0.1 (grey line) is generally considered acceptable.
 239 Bottom: the same data as above but showing the actual error in cm for each axis. (F) Plots showing
 240 decoding accuracy as a function of position along each axis in the open field (top row), aligned lattice
 241 (middle row) and tilted lattice (bottom row). Rows are sum normalized, rows or columns with a total
 242 probability less than .01 are not shown. Perfect decoding would result in a dark diagonal band in each

243 plot. Positions are relative to the central node of the lattice mazes or centroid of the open field (red
244 lines).

245 To investigate this reduced vertical resolution at the level of individual place fields we
246 found the three orthogonal 1D Gaussians (parallel to the Cartesian axes) that best described
247 each place field. In the aligned lattice these Gaussians differed in terms of their standard
248 deviation (median X, Y & Z s.d.; 3.0, 2.7 & 4.1, $\chi^2(2) = 15.4$, $p = .0004$, $\eta_p^2 = .023$, K-W) with
249 the vertical Gaussian (parallel to the Z-axis) best described by a larger standard deviation (X
250 vs Z & Y vs Z, $p < .02$, X vs Y, $p > .92$). By contrast, fields in the tilted lattice could be
251 adequately described by three Gaussians with equivalent standard deviation (median X, Y &
252 Z s.d.; 4.2, 3.6 & 4.1, $\chi^2(2) = 5.0$, $p = .08$, $\eta_p^2 = .008$, K-W). However, the same analysis
253 repeated with Gaussians parallel to the axes of the tilted lattice revealed a small but
254 significant difference between the B and C axes, although this was accompanied by a small
255 effect size (Median A, B & C s.d.; 3.5, 4.1 & 3.4, $\chi^2(2) = 7.5$, $p = .023$, $\eta_p^2 = .009$, K-W; A vs
256 B & A vs C, $p > .23$, B vs C, $p = .02$). These effects can be seen in Fig. 3A & D. An
257 independent approach also confirmed that place field activity was broader along the Z-axis
258 of the aligned lattice (Fig. S8E).

259 Next, we investigated whether this decreased specificity along the vertical dimension
260 might affect the positional accuracy of the information carried by place cells. To test this we
261 used Bayesian decoding to reconstruct an animal's position during a recording session using
262 only the activity of recorded place cells. In total we decoded 9 arena sessions (2 rats,
263 median, min & max total place cells: 37, 29 & 52), 5 lattice maze sessions (1 rat, median,
264 min & max total place cells: 32, 29 & 52) and 4 tilted maze sessions (1 rat, median, min &
265 max total place cells: 44, 39 & 47). In each, the accuracy of decoding exceeded the 95th
266 percentile of decoding performed on shuffled data. Furthermore, to quantify decoding
267 accuracy in each dimension we computed a quality factor, where the decoded trajectory was
268 compared to the accuracy of a constant value (see supplementary methods). A quality factor
269 of 0.1 is generally used as a cut-off for acceptable decoding accuracy (11, 12). In the open

270 field session the quality of decoding was equally high for both the X and Y axes (median X &
271 Y quality: 0.89 & 0.87; $\chi^2(1) = 2.78$, $p = .096$, $\eta_p^2 = .15$, FT). However, in the lattice maze
272 decoding quality differed between the three available axes (median X, Y & Z quality: .50, .54
273 & .41; $\chi^2(2) = 8.40$, $p = .015$, $\eta_p^2 = .56$, FT) with the Z-axis decoding at a significantly lower
274 quality than the X, but equivalent to the Y-axis (X vs Y & Y vs Z, $p > .17$, X vs Z, $p = .013$). In
275 the tilted lattice decoding was equally high along all possible axes (median X, Y & Z quality:
276 .53, .57 & .52; $\chi^2(2) = 3.5$, $p = .17$, $\eta_p^2 = .29$, FT; median A, B & C quality: .52, .57 & .55;
277 $\chi^2(2) = 4.5$, $p = .11$, $\eta_p^2 = .38$, FT). These effects can be seen in Fig. 3E. Closer inspection of
278 the decoded trajectories also revealed that decoding was more accurate at the edges of both
279 lattice mazes (Fig. 3F).

280

281

282 **Discussion**

283 This experiment investigated how hippocampal place cells represent three-dimensional,
284 volumetric space in rats, which are predominantly surface-travelling animals. The aim was to
285 see whether all three dimensions would be represented equally, as they are in freely flying
286 bats, implying a volumetric map of space. We used three-dimensional lattice environments
287 where the rats were free to move in any direction, restricted only by the underlying structure
288 of the environment. In one setting the lattice structure was aligned with gravity and in the
289 other it was tilted, enabling us to disentangle restrictions due to gravity from restrictions due
290 to maze structure. We found that place fields packed the lattice space with ovoid fields, in a
291 similar manner to bats, indicating a volumetric map. However the fields were slightly
292 elongated along the maze axes. This was more pronounced in the vertical dimension for the
293 aligned lattice, indicating an interaction between the effects of structure and gravity on place
294 fields. Taken together with previous findings, this suggests that the hippocampal map of
295 three dimensional space is not fixed but is flexibly shaped by environment structure, perhaps
296 via the movement constraints/affordances it provides. Below, we discuss the findings that
297 lead to this conclusion, and its implications.

298 When the lattice was aligned with gravity we found that rats explored using a “layer
299 strategy” in which they fully explored one level before moving to the next, meaning far fewer
300 vertical movements than horizontal ones – this replicates previous findings and is consistent
301 with the notion that animals will execute the easier parts of a multi-stage journey first (10).
302 When the maze was tilted, all three principal axes became sloped relative to gravity and thus
303 equally easy/hard to traverse, and the layer strategy disappeared. We also found that rats
304 spent more time in the lower part of the mazes.

305 In both maze alignments, we found that place fields were distributed evenly
306 throughout the volume of the lattices and had broadly similar properties in vertical vs.
307 horizontal dimensions. They were larger in volume than fields in the open-field arena,

308 suggesting that the hippocampal representation of space scales according to environment
309 demands. This observation supports the multiscale spatial representation proposed by
310 Geva-Sagiv et al. (13). Furthermore, we also observed the same sublinear relationship
311 between environment and place field size as that study; place field size did not scale linearly
312 with the environment but instead at a reduced rate, an effect which has also been reported
313 previously in rats (14). Oddly however, we did not observe a significant increase in the
314 number of place fields exhibited per cell in the lattice maze environments.

315 We next looked at the structure of place fields in the different dimensions, finding that
316 place fields tended to be elongated, as has been generally seen (10, 11). Elongation did not
317 occur in every direction but was almost always in the direction of the maze axes/boundaries.
318 Two related explanations for why this might occur present themselves. One is that the maze
319 boundaries, represented by the termination of the cross-bars, serve to anchor place fields in
320 a similar way to walls and edges in a flat environment, possibly via boundary cells found in
321 the subiculum (12) and medial entorhinal cortex (13). These have been shown to respond to
322 both walls and edges (15, 16) and are able to “reset” the spatial firing of entorhinal grid cells
323 (17). Since the effect of anchoring falls off with distance due to accumulating path integration
324 error, fields should tend to be narrower in the direction orthogonal to the nearest boundary,
325 for which distance to the wall is small, and elongated in the direction that runs between the
326 two more distant boundaries. The other explanation is that perhaps fields tend to be
327 elongated in the direction more frequently traversed by the animals, or that is traversed for a
328 longer continuous time. Since animals can spend relatively little time running directly towards
329 or away from a boundary, but much time running back and forth along it, synaptic plasticity
330 would have more opportunity to “grow” fields along the direction of travel. A similar argument
331 could explain elongation along maze axes, although rats rarely moved vertically in the
332 aligned lattice yet fields were still elongated along this axis. In the present experiment we did
333 not investigate this further by rotating the axes relative to the boundaries, but this would be
334 an interesting task for future experiments.

335 We next looked at whether field elongation was greater in the vertical dimension.
336 Previous research in rats on vertical surfaces found the vertical dimension to be represented
337 differently, although the exact nature of this difference depended on the movement patterns.
338 When the rats climbed on pegs but remained oriented mainly horizontally then place fields
339 were elongated vertically (6), whereas when the animals climbed by clinging to chicken wire
340 and were thus aligned with the wall then place fields were sparser, but no longer vertically
341 elongated (7). In a study of flying bats, fields were not different from spherical (18). In the
342 present experiment we found an increase in place field elongation in the vertical dimension,
343 which was also represented less stably: however this was only when the maze was aligned
344 with gravity, and not when it was tilted. The aligned configuration is the one that induced
345 differential movement patterns, with freer movement in x-y than in z. Putting all these
346 experiments together, the hypothesis emerges that place fields have less resolution in a
347 dimension in which the animal does not freely travel in the direction of its body axis. This
348 might occur if the distance-tracking process is not uniform in all directions but works best in
349 the direction of travel.

350 The heterogeneity of findings in the different mazes points to a fundamental
351 conclusion which is that there is not a fundamental, holistic map of space that permeates
352 three-dimensional space and is sampled by the animal as it moves through the space over
353 various surfaces. This is because no unitary map structure could account for field elongation
354 on the pegboard, field sparsity on the chicken-wire “cling wall” and rather, it seems that a
355 different kind of place cell representation is recruited depending on environment structure
356 and perhaps task demands.

357 Our findings of a volumetric place cell map agree not only with the data from bats but
358 also from recent neuroimaging work in humans, suggesting the encoding resolution for
359 movement along a vertical axis in a lattice maze does not differ greatly from horizontal (19).
360 However behavioral experiments suggest a subtle difference, with an advantage in memory
361 for horizontal as compared to vertical space (4). More recent evidence suggests that people

362 wrongly estimate the position of objects in a well-known building, giving the overall effect of a
363 vertically elongated but horizontally contracted spatial representation (20) which is in
364 agreement with our finding of increased elongation along the vertical dimension (but see
365 (21). The path which participants use to explore a building has also been shown to play a
366 crucial role; people who explore a building by mainly vertical paths were better at recalling
367 the positions of vertically arranged objects than people who explored the same building by
368 mainly horizontal paths (22) supporting the importance of environment affordances in the
369 development of spatial representations.

370 In this paper we have shown that surface-dwelling animals such as rats do have a
371 volumetric representation of space and that this representation exhibits many of the same
372 characteristics as two-dimensional representations. Place fields are elongated parallel to the
373 primary axes of every environment with a slight bias towards vertical elongation and spatial
374 coding and stability are significantly reduced along this dimension, suggesting that these
375 animals may not encode the vertical dimension with equal accuracy. Future research will
376 need to investigate these effects in volumetric animals such as flying bats to determine if
377 spatial maps share a common organization across species or if separate neural mechanisms
378 exist in volumetric animals. Our results point to an important effect of environmental
379 affordances, evidence of which can be seen in other spatial mapping literature. However,
380 more research is needed to tease apart the relationship between affordances, geometry,
381 gravity and behavioral sampling. This could look to combine recordings with behavioral
382 training, to increase sampling of the more difficult vertical dimension. Our results, combined
383 with those from recent experiments on the head direction system (23, 24) suggest that the
384 rodent spatial navigation network may be far better at mapping three-dimensional space
385 than previously thought. This confirms the relevance of rodents such as rats in studying
386 these representations and undermines the view that volumetric animals such as bats are
387 necessary for these experiments. It also opens up new avenues of research and raises
388 questions regarding other spatial cells such as grid and boundary cells in the Subiculum and

389 medial entorhinal cortex. It is difficult to draw direct parallels between grid and place cells,
390 but the strong spatial representations we have observed in place cells points to a strong
391 possibility of distinct spatial representations of volumetric space by grid cells which have yet
392 to be explored.
393

394 **Methods**

395 *Statistics and figures*

396 Statistics and data analysis were performed using Matlab (R2018a, The MathWorks,
397 Inc.) or SPSS (IBM SPSS statistics 25). If data were found to deviate significantly from a
398 normal distribution (Matlab functions *lillietest*, *skewness*, *kurtosis*) we utilised non-parametric
399 tests such as the Wilcoxon signed rank test (WSR, Matlab function *ranksum*), permutation-F
400 test, Kruskal-Wallis (K-W, Matlab function *kruskalwallis*) or Friedman test (FT, Matlab
401 function *friedman*) and post-hoc tests compared average ranks (Matlab function
402 *multcompare*, Bonferroni correction). Otherwise, we used parametric tests and post-hoc
403 tests compared population means (Matlab function *multcompare*, Bonferroni correction).
404 Except in the case of multivariate comparisons where we sought to determine any
405 interaction effects, then we employed generalized linear models using SPSS. Where
406 possible we report effect sizes for each test: partial eta squared (η_p^2 , proportion of variance in
407 the DV explained by an IV) for K-W, FT and ANOVAs; Cohen's U3 (U3, fraction of values in
408 group 1 less than those in group 2 or the test value in a one-sample test) for WSR; odds
409 ratio (OR, the ratio of the odds of an event occurring in one group to the odds of it occurring
410 in another group) for Chi-square tests of equal proportions. Unless otherwise stated all
411 statistical tests are two-tailed. In all figures * = significant at the .05 level, ** = significant at
412 the .01 level, *** = significant at the .001 level. For all box plots red lines denote the sample
413 median, boxes denote interquartile range, whiskers span the full range of the data and
414 markers represent individual data points.

415 *Subjects*

416 Thirteen animals were used for single unit electrophysiological recording (9 in the
417 lattice, 4 in the diagonal lattice), at which point they weighed approximately 400–450 g. All
418 animals were housed for a minimum of 8 weeks in a large (2150mm x 1550mm x 2000mm)

419 cage enclosure, lined on the inside with chicken wire. This was to provide the rats with
420 sufficient experience climbing in a three-dimensional environment. Inside this cage the rats
421 were also given unlimited access to a miniature version of the lattice maze. This was
422 composed of similar lattice cubes (55 x 55 x 55) but with a slightly smaller spacing (11cm)
423 and was oriented to match the experimental version appropriate to the rats (i.e. rats
424 recorded in the aligned lattice were exposed to a miniature aligned lattice, rats recorded in
425 the tilted lattice were exposed to a miniature tilted lattice). Animals were housed individually
426 in cages after surgery and there they were given access to a hanging hammock or climbable
427 nest box for continued three-dimensional experience.

428 The animals were maintained under a 12 hr light/dark cycle and testing was
429 performed during the light phase of this cycle. Throughout testing, rats were food restricted
430 such that they maintained approximately 90% (and not less than 80%) of their free-feeding
431 weight. This experiment complied with the national [Animals (Scientific Procedures) Act,
432 1986, United Kingdom] and international [European Communities Council Directive of
433 November 24, 1986 (86/609/EEC)] legislation governing the maintenance of laboratory
434 animals and their use in scientific experiments.

435 *Electrodes and surgery*

436 A combination of Axona (MDR-xx, Axona, UK) and tripod design (Kubie, 1984)
437 microdrives were used (rats 750, 770, 775 Kubie drives, all other rats Axona drives). Drives
438 supported four or eight tetrodes, each of which was composed of four HML coated, 17 mm,
439 90% platinum 10% iridium wires (California Fine Wire, Grover Beach, CA). Tetrodes were
440 threaded through a thin-walled stainless steel cannula (21 Gauge Hypodermic Tube,
441 Cooper's Needle Works Ltd., UK). Electrode tips were gold plated (Non-Cyanide Gold
442 Plating Solution, Neuralynx, MT) in order to reduce the impedance of the wire from a resting
443 impedance of 0.7–0.9 M Ω to a plated impedance in the range of 180–300 k Ω (200 k Ω being
444 the target impedance).

445 Microdrives were implanted using standard stereotaxic procedures under isoflurane
446 anaesthesia. Hydration was maintained by subcutaneous administration of 2.5 ml 5%
447 Hartman's solution and 1 ml 0.9% saline. Animals were also given an anti-inflammatory
448 analgesia (small animal Carprofen/Rimadyl, Pfizer Ltd., UK) subcutaneously. Electrodes
449 were lowered to just above the CA1 cell layer of the hippocampus (-3.5 mm AP from
450 bregma, ± 2.4 mm ML from the midline, ~ 1.5 mm DV from dura surface). The drive assembly
451 was anchored to the skull screws and bone surface using dental cement. Animals recovered
452 in a chamber, heated to body temperature. Following this, at least one week of recovery time
453 passed before animals were screened for cells. During this week, the animals' food was
454 tapered from free feeding to the pre-surgery level of restriction.

455 *Apparatus*

456 All experiments were conducted in the same room under moderately dimmed light
457 conditions. A detailed description of the room and apparatus can be found in supplementary
458 methods, Fig. S1 and Fig. 1A. Briefly, we used three main pieces of experimental apparatus;
459 a square open field environment ('arena'), a cubic lattice composed of horizontal and vertical
460 climbing bars ('aligned' lattice) and the same lattice rotated to stand on one of its vertices
461 ('tilted' lattice). Rats were recorded freely foraging in the arena for randomly dispersed
462 flavoured puffed rice (CocoPops, Kelloggs, Warrington, UK) and foraging in the lattice maze
463 for malt paste (GimCat Malt-Soft Paste, H. von Gimborn GmbH) affixed to bars of the lattice.

464 *Recording setup and procedure*

465 A detailed description of the recording setup used can be found in supplementary
466 methods. Briefly, single unit activity was observed and recorded using a custom built 64-
467 channel recording system (Axona, St. Albans, UK) and a wireless headstage (custom 64-
468 channel, W-series, Triangle Biosystems Int., Durham, NC) mounted with infrared LEDs. Five
469 infrared sensitive CCTV cameras (Samsung SCB-5000P) tracked the animal's position at all
470 times (see Trajectory reconstruction section of supplementary methods for more details). For

471 experimental sessions, rats were recorded for a minimum of 18 minutes in the arena,
472 followed by a minimum of 45 minutes in one configuration of the lattice and a further
473 minimum 16 minutes in the arena.

474 *Behavioural analyses*

475 Using smoothed and interpolated 3D reconstructed position data we detected when
476 the rat crossed from one 16cm³ lattice maze cubic element to another along each axis. As
477 our maze sessions vary in length these values are expressed as a rate per second. In a
478 more sensitive approach, we calculated the instantaneous three-dimensional heading of the
479 animal as the normalised change in position:

$$\hat{u} = \frac{\vec{u}}{||\vec{u}||}$$

480 where;

$$\vec{u} = (\Delta_X(t), \Delta_Y(t), \Delta_Z(t))$$

481 and;

$$||\vec{u}|| = \sqrt{\Delta_X(t)^2 + \Delta_Y(t)^2 + \Delta_Z(t)^2}$$

482 this gives a unit vector representing the animal's heading at time t . We then projected these
483 vectors on to a unit sphere and extracted position data falling within regions on the surface
484 of the sphere corresponding to the intersection of the sphere and the axes of interest; the
485 Cartesian X (Pitch = 0°, Azimuth = 0° & 180°), Y (Pitch = 0°, Azimuth = 90° & 270°), Z
486 (Pitch = ±180°, Azimuth = 0°) axes and the diagonal lattice maze relative A (Pitch = ±35.26°,
487 Azimuth = -60° & 120°), B (Pitch = ±35.26°, Azimuth = 60° & -120°) and C (Pitch = ±35.26°,
488 Azimuth = -180° & 0°) axes. The regions were equivalent to 60° conic sections centred on
489 each respective axis in one direction from the origin. For each axis we combined the two
490 corresponding directional regions. The length of time spent moving along each of these axes

491 was calculated as the number of position samples falling along each of these axes multiplied
492 by the sampling rate of the system. For this analysis we used only data when the animal was
493 travelling at a speed >20cm/s. The average speed of movement along each axis was
494 calculated separately as the total distance travelled in each axis divided by the total session
495 time.

496 We also calculated the kernel smoothed density estimate of these spherical points
497 using a Von Mises–Fisher distribution. Briefly, the Gaussian used was defined as:

$$g(x) = \frac{e^{(-0.5(\frac{x}{\sigma})^2)}}{\sqrt{2\pi(\sigma)}} \frac{1}{\sigma}$$

498 where x was defined as the inverse cosine of the inner dot product between each vector
499 point and points across a sphere's surface (Matlab function *sphere*) and σ was the standard
500 deviation of the Gaussian, which was set to 10. In this way, the resulting three-dimensional
501 heat plots give a density estimate of points on the sphere, where density is estimated as the
502 sum of the Gaussian weighted distances (along the surface of the sphere) to every data
503 point.

504 For a measure of three-dimensional thigmotaxis we calculated the total length of time
505 spent in the inner and outer half volumes of the lattice – the inner half being an
506 approximately 77cm³ cube centred on the centre of the lattice. For the diagonal lattice, this
507 central cube was rotated to match the geometry of the maze. Dwell time ratio was calculated
508 as the ratio of these two values for each session. For the square arena environment, we
509 omitted the Z-dimension, instead the inner half was defined as the square region with half
510 the surface area of the arena centred on the middle of the maze.

511 To determine if the rats displayed a bias in their occupancy of 3D space, we also
512 calculated the length of time the rats spent in the top and bottom of the two lattice mazes.

513 For this we categorised data as either above the centre node of the lattice (top) or below it
514 (bottom). Dwell time ratio was calculated as the ratio of these two values for each session.
515 As a measure of exploration coverage, for each session we calculated the proportion of
516 lattice maze nodes (climbing bar intersections) enclosed by the convex envelope of that
517 session's position data. For later place field analyses we also estimated the practical volume
518 of the lattice mazes and arena maze as the average volume of these convex hulls.

519 *Firing rate maps*

520 Three-dimensional volumetric firing rate maps were constructed using a similar
521 approach to that reported previously (25). This procedure is outlined in greater detail in
522 supplementary methods.

523 *Place cell criteria*

524 A cluster was classified as a place cell if it satisfied the following criteria in the
525 session with the greatest number of spikes: i) the width of the waveform with the highest
526 amplitude was >250 μ s, ii) the mean firing rate was greater than 0.1 Hz but less than 10Hz
527 and iii) the spatial information content was greater than 0.5 b/s. Spatial information content
528 was defined as:

$$\text{information content} = \sum P_i \left(\frac{R_i}{R}\right) \log_2 \left(\frac{R_i}{R}\right)$$

529 where i is the voxel number, P_i is the probability for occupancy of voxel i , R_i is the mean
530 firing rate for voxel i , and R is the overall average firing rate (26). In combination with these
531 parameters we also manually refined the resulting place cell classification in order to resolve
532 false positives and negatives.

533 *Isolating place fields*

534 Unless otherwise stated, all analyses were performed on the unsmoothed firing rate
535 maps produced using the above method. When detecting place fields, we looked for areas of

536 more than 64 contiguous voxels (a cube with side length 4 voxels, equivalent to 8000 cm³ or
537 20x20x20 cm) with a firing rate greater than 20% of the maximum value in the rate map.
538 Contiguity was defined as a three-dimensional 18-connected neighbourhood, which includes
539 all voxels sharing an edge or face but not only a vertex. This was calculated using the
540 Matlab function *bwlabeln*. Additionally, a place field had to be visited more than 5 times,
541 where a visit was defined as 1 second of contiguous time spent within the place field convex
542 hull.

543 *Place field features*

544 We then extracted the main features of these place fields (Matlab function
545 *regionprops3*). These included the convex volume, which was defined as the number of
546 voxels contained within the smallest convex polygon that could contain the place field and
547 position, which was defined as the centroid, or centre of mass of the field's voxels. We also
548 extracted the field's orientation and principal axes, which were defined as the orientation and
549 major axes of an ellipsoid with the same normalized second central moments as the field
550 region, calculated using its eigenvectors. We also extracted the Cartesian height and width
551 of the fields, defined as the total length of the field region when projected on to the X, Y and
552 Z-axes respectively. We calculated the elongation index of the principal axes as:

$$Elongation = \frac{P1}{0.5(P2 + P3)}$$

553 where $P1$, $P2$ and $P3$ are the principal axes from largest to smallest respectively. This gives
554 a measure of the curvature of the place field; large elongation values represent elongated
555 fields while a value of 1 would represent a sphere. In the case of the arena elongation was
556 calculated using the first two largest principal axes ($P1/P2$). This is because animals were
557 unable to move vertically, trajectories and ratemaps in this environment are flattened
558 vertically and the Z-axis makes little sense from an analytical standpoint. As an additional

559 geometric measure, independent of the axis lengths, we also calculated the sphericity of
560 each place field's convex hull, sphericity was defined as:

$$sphericity = \frac{\pi^{\frac{1}{3}}(6V)^{\frac{2}{3}}}{A}$$

561 where V is the volume of the place field and A is its surface area. A sphericity of 1 would
562 represent a sphere and any deviation from a sphere would result in a value lower than this.

563 *Field orientation*

564 To determine if fields were oriented in three-dimensions along one or more arbitrary
565 axes we projected the place field eigenvectors (and their antipodal equivalents) on to a unit
566 sphere. Using a similar analysis as the one described for position data, we then extracted
567 the number of fields falling within regions on the surface of the sphere corresponding to the
568 intersection of the sphere and the axes of interest; the Cartesian XYZ axes and the lattice
569 maze relative ABC axes. These regions are equivalent to $\sim 60^\circ$ conic sections centred on
570 each respective axis in one direction from the origin, thus for each axis we combined the two
571 corresponding directional regions (which in this case are merely mirror images). As fields
572 were observed to fall in alignment with the XYZ axes in the lattice maze and the ABC axes in
573 the diagonal lattice we computed an 'axis ratio' for comparison. This was defined as:

$$axis\ ratio = (XYZ - ABC)/(XYZ + ABC)$$

574 where XYZ is the total number of fields parallel to the X, Y and Z axes and ABC is the same
575 for the A, B and C axes. For comparison we randomly distributed 1000 points across the
576 surface of a sphere 1000 times and recomputed the above values. If the number of fields
577 aligned with a particular axis exceeded the 99th percentile of this shuffled distribution it was
578 considered to be significantly overrepresented. If the axis ratio of a maze exceeded the 99th
579 percentile of the ratios obtained in the shuffle it was defined as significantly deviating from 0
580 (no axis bias of any kind) and the sign of the observed ratio was taken as the direction of

581 significance (i.e. >0 = bias towards XYZ, <0 = bias towards ABC). Next, we calculated the
582 Von Mises–Fisher kernel smoothed density estimate of these place field vectors across the
583 sphere's surface (as described in Behavioural analyses). These 3D spherical maps are
584 presented in the main text for visualisation only (Fig. 1 & 2).

585 *Bayesian decoding*

586 To further test for any anisotropy that might not be apparent or detectable in the firing
587 fields of place cells, we also performed Bayesian position decoding (see supplementary
588 data) on sessions in which more than 25 place cells were simultaneously recorded using the
589 method outlined by Zhang et al. (27). We simultaneously recorded a sufficiently large sample
590 of place cells in a total of 9 arena sessions (Median, min & max total place cells: 37, 29 &
591 52), 5 lattice maze sessions (Median, min & max total place cells: 32, 29 & 52) and 4 tilted
592 maze sessions (Median, min & max total place cells: 44, 39 & 47).

593

1 **Acknowledgments**

2 This work was supported by a grant from Wellcome (103896AIA) to K.J.

3 **Author contributions**

4 K.J. conceived the study and obtained funding, S.R., R.G. and K.J. designed the
5 protocol, R.G., S.J-A., K.M., A.L. and S.R. performed surgeries and recordings, R.G
6 analyzed data. All authors interpreted data and discussed results. R.G. and K.J. wrote the
7 manuscript. All authors commented and edited the manuscript.

8 **Competing financial interests**

9 KJ is a non-shareholding director of Axona Ltd.

10

11

12

13 **References**

- 14 1. Tolman EC (1948) Cognitive maps in rats and men. *Psychol Rev* 55(4):189–208.
- 15 2. O'Keefe J, Nadel L (1978) *The Hippocampus as a Cognitive Map* (Clarendon Press,
16 Oxford).
- 17 3. Jeffery KJ, Wilson JJ, Casali G, Hayman RM (2015) Neural encoding of large-scale
18 three-dimensional space—properties and constraints. *Front Psychol* 6.
19 doi:10.3389/fpsyg.2015.00927.
- 20 4. Jeffery KJ, Jovalekic A, Verriotis M, Hayman R (2013) Navigating in a three-
21 dimensional world. *Behav Brain Sci* 36(05):523–543.
- 22 5. Finkelstein A, Las L, Ulanovsky N (2016) 3D maps and compasses in the brain. *Annu*
23 *Rev Neurosci* 39:171–196.
- 24 6. Hayman R, Verriotis MA, Jovalekic A, Fenton AA, Jeffery KJ (2011) Anisotropic
25 encoding of three-dimensional space by place cells and grid cells. *Nat Neurosci*
26 14(9):1182–8.
- 27 7. Casali G, Bush D, Jeffery KJ (2019) Altered neural odometry in the vertical dimension.
28 *PNAS*:pii: 201811867.
- 29 8. Gibson JJ (1986) *The Ecological Approach to Visual Perception* (Lawrence Erlbaum
30 Associates).
- 31 9. Yartsev MM, Ulanovsky N (2013) Representation of Three-Dimensional Space in the
32 Hippocampus of Flying Bats. *Science* 340(6130):367–72.
- 33 10. Jovalekic A, et al. (2011) Horizontal biases in rats' use of three-dimensional space.
34 *Behav Brain Res* 222(2):279–288.

- 35 11. Saleem AB, Ayaz A, Jeffery KJ, Harris KD, Carandini M (2013) Integration of visual
36 motion and locomotion in mouse visual cortex. *Nat Neurosci* 16(12):1864–1869.
- 37 12. Glaser JI, Chowdhury RH, Perich MG, Miller LE, Kording KP (2017) Machine learning
38 for neural decoding. *arXiv:170800909 [q-bioNC]*.
- 39 13. Geva-Sagiv M, Las L, Yovel Y, Ulanovsky N (2015) Spatial cognition in bats and rats:
40 from sensory acquisition to multiscale maps and navigation. *Nat Rev Neurosci*
41 16(2):94–108.
- 42 14. Muller RU, Kubie JL (1987) The effects of changes in the environment on the spatial
43 firing of hippocampal complex-spike cells. *J Neurosci* 7(7):1951–1968.
- 44 15. Lever C, Burton S, Jeewajee A, O’Keefe J, Burgess N (2009) Boundary vector cells in
45 the subiculum of the hippocampal formation. *J Neurosci* 29(31):9771–9777.
- 46 16. Solstad T, Boccara CN, Kropff E, Moser MB, Moser EI (2008) Representation of
47 geometric borders in the entorhinal cortex. *Science* 322(5909):1865–1868.
- 48 17. Hardcastle K, Ganguli S, Giocomo LM Environmental boundaries as an error
49 correction mechanism for grid cells. *Neuron* 86(3):827–839.
- 50 18. Yartsev MM, Ulanovsky N (2013) Representation of three-dimensional space in the
51 hippocampus of flying bats. *Science (80-)* 340(6130):367–372.
- 52 19. Kim M, Jeffery KJ, Maguire EA (2017) Multivoxel Pattern Analysis Reveals 3D Place
53 Information in the Human Hippocampus. *J Neurosci* 37(16).
- 54 20. Brandt T, et al. (2015) “Taller and Shorter”: Human 3-D spatial memory distorts
55 familiar multilevel buildings. *PLoS One* 10(10):e0141257.
- 56 21. Wilson PN, Foreman N, Stanton D, Duffy H (2004) Memory for targets in a multilevel

- 57 simulated environment: Evidence for vertical asymmetry in spatial memory. *Mem*
58 *Cognit* 32(2):283–297.
- 59 22. Dollé L, Droulez J, Bennequin D, Berthoz A, Thibault G (2015) How the Learning Path
60 and the Very Structure of a Multifloored Environment Influence Human Spatial
61 Memory. *Adv Cogn Psychol* 11(4):156–162.
- 62 23. Page HJI, Wilson JJ, Jeffery KJ (2018) A dual-axis rotation rule for updating the head
63 direction cell reference frame during movement in three dimensions. *J Neurophysiol*
64 119:192–208.
- 65 24. Laurens J, Angelaki DE (2018) The brain compass: A perspective on how self-motion
66 updates the head direction cell attractor. *Neuron* 97:275–289.
- 67 25. Leutgeb S, et al. (2005) Independent codes for spatial and episodic memory in
68 hippocampal neuronal ensembles. *Science* (80-) 309(5734):619–623.
- 69 26. Skaggs WE, McNaughton BL, Wilson MA, Barnes CA (1996) Theta phase precession
70 in hippocampal neuronal populations and the compression of temporal sequences.
71 *Hippocampus* 6(2):149–172.
- 72 27. Zhang K, Ginzburg I, McNaughton BL, Sejnowski TJ Interpreting neuronal population
73 activity by reconstruction: unified framework with application to hippocampal place
74 cells. *JNeurophysiol* 79(2):1017–1044.

75