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Neural firing patterns are more schematic and less sensitive to changes in background visual scenes in the subiculum than in the hippocampus

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36   **Abstract**

37

38   Literature suggests that the hippocampus is central to processing visual scenes to remember

39   contextual information, but the roles of its downstream structure, subiculum remain

40   unknown. Here, single units were recorded simultaneously in the dorsal CA1 and subiculum

41   while male rats made spatial choices using visual scenes as cues in a T-maze. The firing

42   fields of subicular neurons were schematically organized following the task structure, largely

43   divided into pre-choice and post-choice epochs, whereas those of CA1 cells were more

44   punctate and bound to specific locations. When the rats were tested with highly familiar

45   scenes, neurons in the CA1 and subiculum were indistinguishable in coding the task-related

46   information (e.g., scene, choice) through rate remapping. However, when the familiar scenes

47   were blurred parametrically, the neurons in the CA1 responded sensitively to the novelty in

48   task demand and changed its representations parametrically following the physical changes of

49   the stimuli, whereas these functional characteristics were absent in the subiculum. These

50   results suggest that the unique function of the hippocampus is to acquire contextual

51   representations in association with discrete positions in space, especially when facing new

52   and ambiguous scenes, whereas the subiculum may translate the position-bound visual

53   contextual information of the hippocampus into schematic codes once learning is established.

Significance statement

Although the potential functional significance has been recognized for decades for the subiculum, its exact roles in a goal-directed memory task still remain elusive. In the current study, we present experimental evidence that may indicate that the neural population in the subiculum could translate the location-bound spatial representations of the hippocampus into more schematic representations of task demands. Our findings also imply that the visual scene-based codes conveyed by the hippocampus and subiculum may be identical in a well-learned task, whereas the hippocampus may be more specialized in representing altered visual scenes than the subiculum.

Introduction

The hippocampus is important to remember an episodic event (Eichenbaum, 2000) and for spatial navigation (O'Keefe and Nadel, 1978). Prior studies have discovered that place cells in the hippocampus play key roles in these cognitive functions (Hasselmo and Schnell, 1994; Treves and Rolls, 1994; Lee et al., 2004). In contrast, the roles of the immediate output region of the hippocampus, the subiculum, are relatively unknown. Anatomically, the subiculum sits at an important position that might be suitable to send hippocampal information to other cortical areas (Witter et al., 2000, 2014). Some studies recording single units in the subiculum in rats have discovered that subicular neurons exhibit spatial firing patterns during foraging (Sharp and Green, 1994). However, their exact firing patterns were different from those of the place cells in the hippocampus (Sharp, 1997, 1999). In addition, some neural correlates of spatial navigation in the subiculum have been reported, including border cells (Lever et al., 2009) and axis-tuned cells (Olson et al., 2017). Other studies have also reported some differential firing patterns between the hippocampus and subiculum in a memory task (Hampson and Deadwyler, 2003). Despite these findings, a coherent theoretical framework is still missing to understand the functional significance of the subicular firing patterns in relation to those in the CA1.

Here, we examined the differential firing patterns of neurons recorded from the dorsal subiculum and CA1 in a visual scene memory (VSM) task (Kim et al., 2012a; Delcasso et al., 2014). To our knowledge, the neural firing patterns of subicular cells in association with purely visual changes in the animal's background have never been reported. Specifically, we tested whether scene-associated rate remapping occurred in the subiculum in the VSM task. We reported previously that the single units in the hippocampus responded to changes in the animal's visual background through "rate remapping" (Delcasso et al., 2014). Rate remapping has been considered as a hippocampal neural code to represent non-spatial or subtle spatial changes in the environment (Leutgeb et al., 2005; Colgin et al., 2008). Rate remapping may occur across different areas in the brain because our previous study showed that the scene-associated rate remapping also occurred in the dorsomedial striatum when single units were recorded from that area and the hippocampus simultaneously (Delcasso et al., 2014). We investigated whether the subicular neurons also show differential correlates

95   compared to hippocampal units in the VSM task when rats performed the task using highly

96   familiar and novel visual scenes.

97

98

99   **Materials and Methods**

100

101   *Subjects*

102   Seven male Long-Evans rats weighing 300–400 g were used. Food was restricted to maintain

103   body weight at 85% of free-feeding weight, and water was available *ad libitum*. Animals

104   were housed individually under a 12-h light/dark cycle. All protocols used are in compliance

105   with the Institutional Animal Care and Use Committee of Seoul National University.

106

107   *Behavioral apparatus*

108   An elevated, T-shaped linear track (47 × 8 cm stem for one rat and 73 × 8 cm stem for others

109   with two 38 × 8 cm arms) containing a food well (2.5 cm in diameter and 0.8 cm deep) at the

110   end of each arm was used in the VSM task (**Figure 1A**). A guillotine door-operated start box

111   (22.5 × 16 × 31.5 cm) was attached at the bottom of the stem. Three LCD monitors were

112   installed as an array surrounding the upper portion of the track to display visual scene stimuli.

113   Four optic fiber sensors (Autonics, Korea) were installed along the track at a distance 1, 27,

114   47 and 67 cm from the entrance of the start box to detect the animal's position and to control

115   the onset and offset of scenes. Additional optic sensors were installed inside food wells to

116   record the moment the rat obtained the reward. Sensor activity was transmitted to a data-

117   acquisition system (Digital Lynx SX, Neuralynx) as TTL signal. We used custom-written

118   software created in MATLAB (MathWorks) and Psychtoolbox to control scene stimuli and

119   transmit TTL signals associated with trial information (e.g., scene stimuli, choice accuracy)

120   to the data-acquisition system. The experimental room was dimly lit by a ceiling lamp. A

121   digital camera attached to the ceiling recorded both positions and directions of the animal's

122   head at a sampling rate of 30 Hz. Black curtains surrounded the apparatus, and white noise

123   was played by two loudspeakers (80 dB) during behavioral sessions to mask unwanted

124   environmental noise.

5

125

126   *Visual scene memory (VSM) task*

127   In the VSM task, the experimenter started a trial by opening the door of the start box. This

128   opening was detected by the optical sensor, immediately triggering the display of the visual

129   scenes on the monitors. The rat ran along the track toward the end of the stem to choose

130   either the left or right arm in association with the visual scene (**Figure 1A**). The food well in

131   the arm that was correctly associated with the scene contained a quarter piece of cereal

132   reward (Froot Loops, Kellogg's), and the rat obtained the reward by displacing a black

133   acrylic disk covering the food well. If the rat made an incorrect choice, no reward was

134   provided, and the rat was gently guided back to the start box immediately after the incorrect

135   choice was made. An inter-trial interval (10 s) was given after a correct trial; a longer (20 s)

136   inter-trial interval was applied after an incorrect choice was made. The experimenter placed a

137   reward in one of the food wells for the next trial (following the pre-determined baiting

138   sequence) during the intertrial interval. The rat was confined in the start box during the

139   intertrial interval, and the high walls (31.5 cm) and background white noise (80 dB) in the

140   room made it difficult for the rat to discern the next trial's baited food-well location from the

141   start box.

142   Four grayscale visual patterns (zebra stripes, pebbles, bamboo, snow-covered

143   mountains) were used as scene stimuli. The visual scenes were equalized for luminance (set

144   at an average intensity value = 103 in Adobe Photoshop). For all trials, zebra stripes and

145   bamboo patterns were associated with the left food well, and pebbles and mountain patterns

146   were associated with the food well in the right arm (**Figure 1A**). Rats were initially trained to

147   criteria with a pair of visual scenes (≥75% correct choices for each scene for two consecutive

148   days) and then were trained with the second pair of scenes. The training order for the use of

149   different scene pairs was counterbalanced among the rats. Forty trials were given in a pre-

150   surgical training session. The presentation sequence of scene stimuli across trials in a given

151   session was pseudo-randomized with the following constraints: 1) each scene was presented

152   equally in every 20 trials, and 2) the same food well was not used for rewards in four

153   consecutive trials. Once rats learned both pairs of scene stimuli according to criterion (≥75%

154   correct choices for all scenes for two consecutive days; **Figure 1B**), a hyperdrive was

155   implanted.

156

6

157 *Hyperdrive implantation*

158 After behavioral training, a hyperdrive carrying 24 tetrodes and 3 reference electrodes was

159 implanted for recording single-unit spiking activities simultaneously from the dorsal CA1 and

160 subiculum. The impedance of each tetrode was adjusted to 100–300 kΩ (measured in gold

161 solution at 1 kHz with an impedance tester) 1 day before the hyperdrive was implanted. For

162 surgery, the rat was anesthetized with an intraperitoneal injection of sodium pentobarbital

163 (Nembutal, 65 mg/kg) and its head was fixed in the stereotaxic frame (Kopf Instruments,

164 USA). Inhalation of isoflurane (0.5-2% isoflurane mixed with 100% oxygen) was used to

165 maintain the anesthesia throughout surgery afterwards. Before making an incision along the

166 longitudinal midline of the scalp, the scalpel blade and the incision area was sprayed with

167 benzocaine for local anesthesia. A burr hole was drilled into the skull on the right hemisphere

168 to insert the bundle of the hyperdrive. The target coordinates for implantation was pre-

169 determined to allow the tetrodes to cover a range from 3.48 to 6.6 mm posterior to bregma

170 and from 1 to 3 mm lateral to the midline. Then, the hyperdrive was chronically affixed to the

171 skull by applying bone cement to its bundle and multiple skull screws near the bundle. After

172 surgery, ibuprofen syrup was orally administered to control the animal's general pain and the

173 rat was left in a veterinary intensive care unit in which temperature and humidity were strictly

174 controlled. More detailed surgical procedures can be found in our previous studies (Delcasso

175 et al., 2014; Ahn and Lee, 2015).

176

177 *Electrophysiological recording*

178 After a week of recovery from surgery, rats were re-trained (~160 trials per session using the

179 same pairs of scenes used before surgery) until they showed stable performance ($\geq$75%

180 correct choices for each scene); over the course of a number of days during this period,

181 tetrodes were gradually lowered into target areas. For tetrode adjustments, each rat was

182 placed on a pedestal in a custom-made aluminum booth outside the behavioral testing room,

183 and the adjustment of tetrodes began. Neural signals were transmitted through the headstage

184 (HS-36, Neuralynx) and tether attached to the electrode interface board of the hyperdrive to

185 the data-acquisition system. Neural signals were digitized at 32 kHz (filtered at 600–6,000

186 Hz) and amplified 1000–10,000 times. Tetrodes were lowered daily by small increments to

187 reach the target areas and to maximize the number of single units recorded per tetrode.

188   Once the main electrophysiology recording session began, all four scenes shown

189 during the training period were presented in an intermixed fashion within a standard session

190 (STD; ~160 trials per session). During the behavioral task, neural signals were relayed

191 through a slip-ring commutator to the data-acquisition system, and an array of green and red

192 LEDs was attached to the headstage to monitor the animal's positions and head directions

193 using a ceiling camera (sampling rate, 30 Hz). After the rats performed well in STD sessions

194 (~3–4 days), a blurred version of the task (Blur) began. In the Blur session, rats (n = 6;

195 recordings were not obtained for one rat in the Blur session) performed the task with zebra

196 and pebbles scenes for 20 trials (STD block). Then, beginning with trial 21, modified

197 versions of the original scenes (30% and 50% Gaussian-blurred images) were presented with

198 the original scenes (i.e., 0% Gaussian-blurred scenes) for the remaining trials of the session

199 (Blur block; 120-160 trials in total per session) (**Figure 1C**).

200

201 *VSM task with masked visual scenes*

202 In a separate group of rats (n = 10), we tested the rat's performance while masking some

203 portions of the visual scenes. This was to test if the rat could solve the task merely by using a

204 local feature of the visual scene instead of using the entire visual pattern. Specifically, rats

205 were first trained to criterion (≥75% correct choices for each scene for two consecutive days)

206 in the VSM task. Then, the rats were tested in a modified version of the VSM task in which

207 normal trials (64 trials) were intermixed with masking trials (16 trials) in a session. In the

208 masking trials, the original visual scene was occluded by a gray sheet with regularly spaced

209 viewing holes through which partial visual patterns were seen by the rat. It is important to

210 note that the masking patterns still enabled the rat to see the overall visual scenes (especially

211 for the masking pattern with larger viewing holes; mask pattern 1 in **Figure 11A**). Four

212 scenes were used in the masking trials. Because two different masking configurations

213 (randomly picked from two pairs of masking configurations as shown in **Figure 11A**) and the

214 sizes of the viewing holes were different from trial to trial, the rat's performance would drop

215 to chance level if the rat learned to solve the task by relying on a particular local feature of

216 the scene instead of the entire pattern.

217

218 *Histology*

219   After the completion of all recording sessions, an electrolytic lesion was made via each

220   tetrode (10 μA current for 10 s) to mark the tip position. After 24 hours, the rat inhaled an

221   overdose of CO_2 and was perfused transcardially, first with phosphate-buffered saline and

222   then with a 4% v/v formaldehyde solution. The brain was extracted and soaked in 4% v/v

223   formaldehyde-30% sucrose solution at 4°C until it sank to the bottom of the container. After

224   post-fixation procedures, the brain was gelatin-coated and soaked in 4% v/v formaldehyde-

225   30% sucrose solution. The brain was sectioned at 30-40 μm using a freezing microtome (HM

226   430; Thermo-Fisher Scientific), after which sections were mounted and stained with thionin.

227   Photomicrographs of brain tissues were taken using a digital camera (Eclipse 80i, Nikon)

228   attached to a microscope, and were reconstructed three-dimensionally to match the

229   configuration of the tetrodes from the initial bundle design. The exact locations of tetrodes

230   were determined using the 3D reconstructed images and physiological depth profiles

231   recorded at the time of data acquisition. To better present tetrode positions, we constructed a

232   flat map of the dorsal CA1 and subiculum using Nissl-stained coronal sections and marked

233   the tetrode positions in all rats in the flat map.

234

235   *Construction of a flat map*

236   A flat map was constructed using the coronal brain sections from all rats (**Figure 2A**). Nissl-

237   stained sections were aligned to orient tetrode tracks vertically, and the length of the cell

238   layer in the subiculum and CA1 of each section was measured using *Image J* software.

239   Because the cell layer was curved along the transverse axis, multiple dots were first marked

240   along the cell layer at narrow intervals, and the distance between the dots was calculated by

241   summing their x and y positions. The marking procedures for dots started from the most

242   distal end of the subiculum or CA1 and proceeded toward the proximal border. The lateral

243   border of the flat map was based on the measured lengths of cell layers along the anterior-

244   posterior axis. Because of individual differences in brain sizes and sectioning angles among

245   rats, flat maps for all rats were proportionally adjusted by using the medial habenular nucleus

246   and superior colliculus as references (Paxinos and Watson, 2009). After normalizing along

247   the anterior-posterior axis, the length of the cell layer was finally determined by taking the

248   median value of distances measured for all rats. The relative tetrode tip positions were then

249   marked on the flat map.

250

251 *Unit isolation*

252 Single units were simultaneously recorded from the dorsal CA1 (n = 364) and dorsal

253 subiculum (n = 320), and were isolated manually using both commercial (SpikeSort3D,

254 Neuralynx) and custom-written software (WinClust) using multiple waveform parameters,

255 including peak and energy, as previously described (Lee and Kim, 2010; Delcasso et al.,

256 2014). Neurons that did not satisfy the following set of criteria were excluded in further

257 analysis: (*i*) average peak-to-valley amplitude of waveforms ≥ 75 µV (79 units excluded), (*ii*)

258 proportion of spikes within a 1-ms refractory period < 1% of total spikes (5 units excluded)

259 and (*iii*) average firing rate during the outbound journey on the stem ≥ 1 Hz (174 units

260 excluded). In addition, fast-spiking neurons (mean firing rate ≥ 10 Hz; width of the average

261 waveform < 325 µs) were excluded (n = 55) from the analysis. Only those units that met the

262 above criteria (n = 129 in CA1, n = 242 in subiculum) were used for final analysis. The

263 reason behind the larger amount of neurons being filtered out in CA1 (n = 133) than in the

264 subiculum (n = 41) was largely because many cells (approximately half of the isolated

265 clusters) fired sparsely during the outbound journey in CA1, showing lower firing rates (<

266 1Hz), but that was not the case in the subiculum.

267

268 *Data analysis*

269 *(i) Characterizing basic firing properties.* To measure the amount of spatial information

270 conveyed by a unit, we constructed a linearized spatial rate map. Position data from

271 behavioral sessions were scaled down (bin size = 4 cm^2). Then, a raw spatial rate map was

272 constructed by dividing the number of spikes by the duration of visit for each bin. The spatial

273 rate maps were smoothed by moving average method for illustration purpose only. Spatial

274 information was computed according to the following equation (Skaggs and McNaughton,

275 1993):

$$276 \qquad \text{Spatial information} = \sum_i p_i \frac{\lambda_i}{\lambda} \log_2 \frac{\lambda_i}{\lambda} \text{ (bits/spike)},$$

277 where i denotes bin, p_i is occupancy rate in the ith bin, λ_i is the mean firing rate in the ith bin,

278 and λ is the overall mean firing rate. The mean firing rate of a unit was obtained by averaging

279 the firing rates in the raw rate map. Other conventional spatial firing characteristics of cells

280   such as spatial selectivity and sparsity measures were computed using the following formula

281   (Skaggs et al., 1996):

282   $$\text{Sparsity} = \frac{(\Sigma p_i \lambda_i)^2}{(\Sigma p_i \lambda_i^2)}, \quad \text{Selectivity} = \frac{\max(\lambda_i)}{\lambda}$$

283   where the same symbols were used as in the formula for calculating spatial information

284   above. To minimize the effect of animal's behavior on the measurements, we assumed that p_i

285   in the sparsity formulas had uniform distribution on the maze (Jung et al., 1994). Coherence

286   of a place field was computed as z-transforms of correlations between two lists of spatial

287   firing rates (i.e., the firing rate of each spatial bin and average firing rate of each bin's nearest

288   bins) (Muller and Kubie, 1989). Following the previous study (Kim et al., 2012b), a burst

289   index was defined as the power of autocorrelation during 1-6 ms normalized by the power

290   during 1-20 ms.

291

292   *(ii) Construction of an event rate map.* We designated seven sequential task-relevant events

293   as follows: trial start (opening of the door of the start box), three different time points

294   detected by the optic sensors installed along the stem, spatial choice (turning to either the left

295   or right arm), reaching the half point between the moment of spatial choice and reaching the

296   arm end, and displacing the disc overlying the food well that contained reward (**Figure 3A**).

297   Timestamps for individual events were recorded by optic sensors, except for the choice event.

298   Timestamps for the choice event were determined by detecting the spatial bin in which a

299   significant difference between position traces associated with the left and right choice trials

300   (two-sample t-test). The durations of individual events across trials were normalized and

301   were split into three bins. Then, a raw *event rate map* (ERM) was constructed by dividing the

302   number of spikes by the duration of occupancy for each bin (**Figure 3B**). The raw ERM was

303   smoothed using a moving average method to define field boundaries and for illustration

304   purposes. However, all data analysis was conducted using raw ERMs.

305

306   *(iii) Boundaries and categorization of event fields.* ERMs were categorized into three groups

307   based on the number of firing fields; single field (SF), multiple fields (MF) and event-

308   unrelated fields (**Figures 4A** and **4B**). If the minimum firing rate of an ERM was larger than

309   the half maximal firing rate, the rate map was classified as an event-unrelated field and the

11

310   event-unrelated fields were excluded in the following analysis. The directions of change in

311   firing rates across the events were measured by comparing the firing rates before and after the

312   events to determine the boundaries of a field. That is, the firing rate of a bin was statistically

313   compared with the firing rate in the next bin (using Wilcoxon rank-sum test) in an ERM to

314   determine the direction of firing-rate changes (i.e., increase, decrease, and no change). The

315   sequence of the changing direction in firing rate across the events made it possible to define

316   local minima. Within the local minima, the bin with the maximal firing rate was defined as

317   the peak of the field, and the boundaries were defined by detecting the bins in which the

318   firing rates decreased to less than 40% of the peak firing rate. If there was no bin with the

319   firing rate lower than the criteria, the local minimum became a field boundary. After defining

320   the boundaries, cells were classified into two types: that is, a single field (SF) and multiple

321   fields (MF) based on the number of the fields. A field with a ratio of the minimum to

322   maximum firing rates exceeding 0.5 was not considered as a valid field. Field width was

323   measured by counting the number of bins between the boundaries of a field. If there were

324   more than one field in a rate map (i.e., MF), then each field was treated as independent fields.

325

326   *(iv) Autocorrelation matrix.* An autocorrelation matrix was constructed for the cells with

327   single fields (Gothard et al., 1996; Lee et al., 2004) to measure the representation of the task

328   period at the neural population level (**Figure 5B** and **5G**). For this purpose, first, a population

329   rate map consisted of the individual rate maps (each normalized by the cell's maximum firing

330   rate) was prepared, and the correlation between the two vectors from the same population rate

331   map was computed using the following equation for obtaining the Pearson correlation

332   coefficient:

$$R_{ij} = \frac{\sum_{C=1}^{n}(FR_{i,C} - \overline{FR}_i)(FR_{j,C} - \overline{FR}_j)}{\sqrt{\sum_{C=1}^{n}(FR_{i,C} - \overline{FR}_i)^2}\sqrt{\sum_{C=1}^{n}(FR_{j,C} - \overline{FR}_j)^2}}$$

334   where *i* and *j* denote the population vector from the population rate map, *n* is the number of

335   cells, *C* indicates *C*-th cell in the population, *FR* is the firing rate of the cell, and $\overline{FR}$ is the

336   mean firing rate of the vector. As a result, a symmetric matrix was obtained, and the matrix

337   space was then divided into task-congruent (TC) and task-incongruent (TI) sections (**Figure

338   5C**). Specifically, the task-congruent area denotes the subregion of the correlation matrix in

339   which the correlation coefficients were calculated between the same task epochs (e.g.,

340   between pre-choice and pre-choice epochs), and the task-incongruent area represents the

341   region in which the correlation coefficients were obtained between different task epochs (e.g.,

342   between pre-choice and post-choice epochs). Then, the correlation coefficients associated

343   with the two areas were statistically compared using the Wilcoxon rank-sum test.

344

345   *(v) Procedures for random shifting of ERM.*   The locations of individual firing fields in the

346   population ERM were shuffled while the sizes of individual fields were maintained.

347   Specifically, the ERMs of individual cells were shifted by random amounts of bins in either

348   forward or backward direction, and the resulting ERMs were realigned (**Figure 5F**). The

349   range of shifting was restricted so that the individual field boundaries did not exceed the

350   boundaries of the population ERM after shifting. To compare the effects of the random

351   shifting of individual fields both in the CA1 and subiculum, we measured the similarity of the

352   resulting autocorrelation matrix (**Figure 5G**) with the original autocorrelation matrix (**Figure

353   5B**) by calculating a Pearson correlation coefficient. Then, the shifting procedure was

354   repeated for 1000 times, and the Pearson correlation coefficient was calculated each time

355   using the original autocorrelation matrix as a counterpart. The resulting distributions of

356   correlation coefficients were compared by a Wilcoxon rank-sum test in the CA1 and

357   subiculum.

358

359   *(vi) Speed analysis.* The rat's positions were recorded at 30 Hz in the current study. We

360   divided the length of the three consecutive points by the duration of time to calculate the

361   instantaneous running speed, and assigned the speed value to the middle point of the three.

362   For constructing the speed map of a session, the instantaneous running speeds were averaged

363   for each event bin as when constructing an ERM. The speed map before the track entrance

364   event was not available because the matching position data were not sampled inside the start

365   box in our experimental setup. Then, we defined that a cell's firing pattern was speed-

366   correlated when the following criteria were met: (*i*) the Pearson correlation coefficient

367   calculated between the speed map and ERM was both positive and statistically significant,

368   and (*ii*) the Pearson correlation coefficient between the in-field firing rate for each trial and

369   its associated speed was both positive and significant. For calculating the in-field firing rate

370   or the in-field running speed, only the data obtained before the choice event were used

371   because the running speeds were systematically different between the two arms.

13

372

373 *(vii) Rate difference index (RDI).* We obtained an RDI to measure the amount of rate

374 modulation between two rate maps by calculating an absolute value of Cohen's d:

375 $$\text{Rate difference index (RDI)} = \left| \frac{mean(FR_1) - mean(FR_2)}{std(FR_1, FR_2)} \right|,$$

376 where FR_1 and FR_2 denote the in-field firing rates of the trials associated with two different

377 conditions, respectively. Since the Cohen's d measure is a standardized measure that includes

378 a term for standard deviation in the denominator, a possible confounding effect induced by

379 the variability in intrinsic firing should be controlled in our analysis. The difference in firing

380 rates between the left and right choice trials was computed as RDI$_{CHOICE}$ (**Figure 8A**).

381 RDI$_{SCN}$ was calculated as the difference of the two rate maps associated with different scenes

382 that shared the same choice response (e.g., RDI$_{SCN-L}$ for the zebra-bamboo scene pair and

383 RDI$_{SCN-R}$ for the pebbles-mountain pair; the bigger of the two taken) (**Figure 8B**). For

384 analyzing the rate modulation in the blurred version of VSM task, RDI between STD and No-

385 Blur conditions was computed. In addition, RDI$_{SCN-C}$ values between the zebra and pebbles

386 scenes for different blur conditions (No-Blur, Lo-Blur, and Hi-Blur) were separately

387 obtained.

388

389 *Experimental design and Statistical analysis*

390 Seven male Long-Evans rats were used in the VSM task (29 sessions in total). Two sessions

391 were excluded because of the malfunctioning optic sensors. Six rats experienced the blurred

392 version of the VSM task. Each rat was tested only once in the blurred VSM task to minimize

393 learning effects. Neural spiking data were analyzed using nonparametric statistics and a

394 Bonferroni correction procedure was used during post-hoc tests involving multiple

395 comparisons. Testing for statistical significance was two-sided, except when testing

396 significance against known criteria (e.g., behavior performance criterion of 75% or chance

397 performance level of 50%). The level of statistical significance was set at $\alpha = 0.05$ unless

398 noted otherwise. Behavioral performance levels for different scene stimuli or different blur-

399 levels were compared using a repeated-measures ANOVA (paired t-test for *post-hoc*

400 analysis). A one-sample t-test was used to compare performance against our performance

401 criterion. Comparisons of basic firing properties and field size between two regions (e.g.,

14

402 CA1 and subiculum) were conducted using a Wilcoxon rank-sum test. A Pearson's chi-

403 square test was used to compare the proportions of cell types in the CA1 and subiculum.

404 Comparisons of the correlation coefficients in the task-congruent or task-incongruent

405 condition between two regions were conducted using Wilcoxon rank-sum tests. The

406 Wilcoxon rank-sum test was also used to compare RDI_{CHOICE}, RDI_{SCN}, and RDI (between

407 STD and No-Blur conditions) between two regions. When comparing the firing rates between

408 STD and No-Blur conditions, the Wilcoxon rank-sum test was used. The Pearson's chi-

409 square test was used to compare the proportions of cells that underwent significant rate

410 modulations. Differences in RDI_{SCN-C} among blur conditions were assessed using a Kruskal-

411 Wallis test, with the application of the Wilcoxon rank-sum test for post-hoc comparisons. The

412 Kruskal-Wallis test was also used for comparing RDI_{SCN-C} (No-Blur & Lo-Blur conditions)

413 between the CA1 and subiculum.

414

415

416 **Results**

417

418 **Simultaneous recording of single units from the CA1 and subiculum in the VSM task**

419 Single units were recorded simultaneously from both the CA1 and subiculum while rats

420 performed the VSM task in which four visual scenes were presented in a pseudo-random

421 sequence on three adjacent monitors surrounding the T-maze (**Figure 1A**). The rat was

422 required to choose either the left or the right arm associated with a given visual scene. By the

423 time when the main recording session began, all rats made correct choices in more than 85%

424 of the trials for all scene stimuli, and performance for all scenes exceeded the criterion of

425 75% (*P*-values < 0.0001, one-sample t-test) (**Figure 1B**).

426   We reconstructed the locations of tetrode tips on a flat map (**Figures 2A**), using both

427 histological results (**Figure 2B**) and physiological recording profiles. The recording locations

428 were distributed approximately 3.5 to 6.6 mm posterior to bregma. The units that satisfied our

429 unit-isolation criteria (n = 129 in CA1; n = 242 in subiculum) were found along the entire

430 proximodistal axis in both CA1 and subiculum although more CA1 units were recorded in the

431 proximal portion than in the distal part. There was a narrow zone at the border between the

432 distal CA1 and the proximal subiculum where cell layers of both regions overlapped

433   (SUB/CA1 in **Figure 2A** and **2B**). We assigned the units recorded from this region to either

434   CA1 or subiculum using multiple criteria, including *(a)* the baseline firing rate recorded in

435   the start box in the absence of the scene stimulus (< 1 Hz in the CA1 and > 4 Hz in the

436   subiculum), *(b)* the morphological characteristics of the cell layers in Nissl-stained sections,

437   and *(c)* the depth-profiles for individual electrodes recorded during the tetrode-adjustment

438   period. As reported in prior studies (Barnes et al., 1990; Sharp and Green, 1994; Kim et al.,

439   2012b), the mean firing rate was higher on average in the subiculum than in the CA1 (Z =

440   6.83, *P* < 0.0001, Wilcoxon rank-sum test) (**Figure 2C**). In addition, units recorded from the

441   CA1 bursted more (Z = 12.91, *P* < 0.0001, Wilcoxon rank-sum test) and fired more spatially

442   (spatial information score: 1.12 ± 0.06 in CA1, 0.25 ± 0.02 in subiculum; sparsity: $0.43 \pm$

443   0.02 in CA1, 0.78 ± 0.01 in subiculum; coherence: 1.81 ± 0.05 in CA1, 1.34 ± 0.04 in

444   subiculum; spatial selectivity: 4.34 ± 0.18 in CA1, 2.14 ± 0.07 in subiculum; Mean $\pm$ S.E.M.;

445   *P*-values < 0.0001, Wilcoxon rank-sum test) than the units recorded from the subiculum

446   (**Figure 2C**).

447

448

449   **Single units in the CA1 and subiculum responded to task-relevant events**

450   Subicular cells are known to show relatively poor spatial firing compared to hippocampal

451   cells in general (Barnes et al., 1990; Sharp and Green, 1994), which was also the case in the

452   current study. Therefore, we decided to organize the neural firing patterns by using the

453   critical events that occurred in the task (Aronov et al., 2017), instead of using location-based

454   neural representations. We named such a neural representation "*event rate map (ERM)*" in the

455   current study. To construct an ERM, we defined three critical events associated with task

456   demands as follows: *(a)* 'S' - opening of the door of the start box (which also corresponded to

457   the onset of the scene stimulus, detected online by an optic sensor), *(b)* 'C' – choosing the left

458   or right arm at the intersection (detected offline by calculating the position-diverging point),

459   and *(c)* 'R' - displacing the disc that covered the food well containing reward (detected online

460   by optic sensors) (**Figure 3A**). We also used the activities from three additional sensors and

461   the bisecting point between the choice point and reward location as minor events to construct

462   individual ERMs. Therefore, an ERM is composed of seven time points associated with the

463   abovementioned seven events (**Figure 3B**) and the six event epochs between those time

464   points. Constructing an ERM enabled us to analyze the neural firing patterns recorded

465   immediately before and after the door-opening event in the start box (which coincided with

16

466   the onset of a scene stimulus) while capturing the spatial firing characteristics at the same

467   time (**Figures 3C** and **3D**).

468   Examining the individual ERMs of the CA1 and subiculum showed some differences

469   between the two areas. Specifically, most units in the CA1 showed a single field occupying a

470   narrow zone seemingly corresponding to the size of a single event epoch in the ERM ('SF' in

471   **Figure 4A**). Some units fired at multiple epochs in the ERM in the CA1 ('MF' in **Figure 4A**)

472   although there were not many such cases. In contrast, subicular units tended to fire across

473   contiguous epochs in the ERM, resulting in longer single firing fields ('SF' in **Figure 4B**) or,

474   when firing in multiple epochs separated from each other, multiple firing fields ('MF' in

475   **Figure 4B**). In some units, we could not detect event-related fields (event-unrelated units; see

476   Materials and Methods) and we excluded those units for analysis in the current study. Most

477   CA1 units showed single fields (> 80%), whereas the units exhibiting single fields and

478   multiple fields were almost equally found in the subiculum ($\chi^2_{(1)}$ = 49.69, P < 0.001, Chi-

479   square test) (**Figure 4C**). The sizes of event-related fields in the CA1 and subiculum were

480   also statistically different from each other ($\chi^2_{(2)}$ = 75.92, P < 0.0001, Kruskal-Wallis test;

481   *inset* in **Figure 4D**). Specifically, the size of single fields in the CA1 was significantly

482   smaller than that of the single fields in the subiculum (SF: Z = 8.09, P < 0.0001; single fields

483   within MF: Z = 2.63, P < 0.01; Wilcoxon rank-sum test), and single fields in the subiculum

484   were larger than the individual fields of the multiple fields in the subiculum (Z = 7.27, P <

485   0.0001).

486   Interestingly, the proximal region of the subiculum contained more multiple-field

487   units than single-field units and *vice versa* in the distal subiculum (Z = 2.16, P = 0.033,

488   Wilcoxon rank-sum test) (**Figure 4E**). These might be attributable to the fact that the distal

489   portion of the subiculum receives stronger inputs from the medial entorhinal cortex, whereas

490   the proximal subiculum receives more inputs from the lateral entorhinal cortex (Cembrowski

491   et al., 2018).

492

493   **Neural populations in the subiculum fired schematically, capturing the task structure**

494   **better than those in the CA1**

495   To examine the information structure conveyed by the neural populations in the subiculum,

496   we constructed a population ERM by combining all the individual ERMs (aligned according

497 to their maximal firing locations along the entire task period) both for the CA1 and subiculum

498 (**Figure 5A**). Because the relative lack of the units showing multiple fields in the CA1, only

499 the units whose ERMs showed single fields were analyzed in both CA1 and subiculum. As

500 expected from the individual ERMs, event-related fields covering individual epochs were

501 linearly aligned from the trial start (S) to goal-reaching (R) event in the neural population in

502 the CA1. In contrast, individual fields were wider in the population ERM in the subiculum,

503 particularly in the periods starting from the start box opening (S) to the spatial choice (C),

504 and from the spatial choice (C) to the reward location (R).

505   We then computed an autocorrelation matrix by cross-correlating the population ERM

506 with itself to show the amount of correlation in the population firing patterns between

507 different event periods (**Figure 5B**). There was a narrow, high correlation band (seemingly

508 matching the size of an event epoch in the ERM) along the diagonal in the CA1. However, in

509 the subiculum, the autocorrelation matrix clearly showed two rectangular, high-correlation

510 regions (i.e., *task-congruent regions*) corresponding to the pre-choice and post-choice epochs

511 of the task. Furthermore, the correlation was relatively lower in the areas where the

512 population rate maps in the pre-choice period were correlated with those in the post-choice

513 period, and *vice versa* (i.e., *task-incongruent region*). It appears that the neural population in

514 the subiculum "schematically" represented the most critical two epochs of the task; that is,

515 the pre-choice (from stimulus onset to choice) and post-choice (from choice to reward)

516 epochs in a given trial. The average amount of correlation in the task-congruent regions

517 (orange triangular areas in **Figure 5C**) in the autocorrelation matrix was greater in the

518 subiculum than in the CA1 ($Z = 4.30$, $P < 0.0001$, Wilcoxon rank-sum test; **Figure 5D**). In

519 contrast, the correlation was significantly lower in the task-incongruent area (blue rectangular

520 area in **Figure 5C**) in the subiculum than in the CA1 ($Z = 3.85$, $P < 0.0001$, Wilcoxon rank-

521 sum test; **Figure 5E**).

522   Next, we tested if the schematic representation of the subiculum could be mainly

523 attributable to the broader firing patterns of subicular cells compared to CA1 neurons. To test

524 it, we obtained the population ERM whose individual fields were randomly shifted and

525 realigned (**Figure 5F**), and calculated an autocorrelation matrix based on the shifted

526 population ERMs (**Figure 5G**) both in the CA1 and subiculum (repeated for 1000 times; see

527 Materials and Methods for details). Figure 6G shows the representative autocorrelation

528 matrices obtained for the CA1 and subiculum using the above procedures, and it is clear that

18

529   the surrogate autocorrelation matrices for both CA1 and subiculum now exhibit similar,

530   symmetric shapes of high-correlation zones along the diagonal direction (**Figure 5G**) as was

531   observed in the CA1 when using the original population ERMs (**Figure 5B**). That is, the

532   distinct patterns of high-correlation areas, separated by the choice point, in the

533   autocorrelation matrix of the subiculum disappeared as the field positions were shifted. When

534   we compared the similarity of the autocorrelation matrices between the original and shifted

535   versions by calculating pixel-to-pixel correlations, the autocorrelation matrices composed of

536   randomly shifted subicular ERMs were more similar to that of the CA1 than that of the

537   subiculum ($Z = 38.72$, $P < 0.0001$, Wilcoxon rank-sum test). These results suggest that the

538   schematic firing patterns of the subiculum may not be explained simply by the large field

539   sizes of the subiculum.

540   Furthermore, we checked the possibility that the running speed of animal might have

541   driven the schematic firing patterns of the subiculum described above. For this purpose, we

542   tested whether a given cell's firing rate was significantly correlated with the animal's running

543   speed. Specifically, we first picked the cells in which the ERM and its associated speed map

544   were significantly correlated. Then, among those cells, we checked whether the cell's in-field

545   firing rates for individual trials were significantly correlated with their associated running

546   speeds (**Figure 5H**). The cells meeting these two criteria were labeled as 'speed cells' and we

547   found some speed cells both in the CA1 (11%, n = 12/109) and subiculum (6%, n = 6/101).

548   Importantly, excluding these cells led to the almost same results (*P-values* < 0.001 when

549   comparing the correlation coefficients of the two regions in the task-congruent and task-

550   incongruent zones).

551   These findings suggest that the schematic neural firing patterns uniquely found in the

552   subiculum compared to the CA1 (**Figure 6**) cannot be explained simply by the running speed

553   of rats in our study.

554

555   **When visual scenes are highly familiar, neurons in both CA1 and subiculum were**

556   **equally capable of representing visual scenes differentially using rate modulation**

557   We examined whether scene-based rate remapping also occurred in the subiculum when

558   facing different visual scenes as we previously reported in the dorsal CA1 (Delcasso et al.,

559   2014). Because no significant difference was found during analysis between the single-field

560   and multiple-field types in the subiculum, all ERMs were used in the subiculum for analysis.

561   Confirming our prior findings (Delcasso et al., 2014), when familiar visual stimuli were used

562   in the VSM task, some units in the CA1 exhibited robust rate remapping according to the

563   rat's choice response (**Figure 7A**, cells 4-6). In contrast, other units' firing rates were

564   modulated by visual scenes (when comparing between different scenes associated with the

565   same choice response) (**Figure 7A**, cells 7-9). Importantly, similar rate remapping patterns

566   were also found in the subiculum. That is, some subicular neurons changed their firing rates

567   according to the rat's choice (**Figure 7B**, cells 13-15) and other units were more tuned to the

568   visual scenes (**Figure 7B**, cells 16-18). In both regions, some cells were not responsive to

569   task demands ('nonspecific units' in **Figures 7A** and **7B**).

570   To measure the amount of rate remapping, we developed a rate difference index

571   (RDI) as follows. The RDI between the two choices (RDI$_{CHOICE}$) was obtained by calculating

572   the absolute difference between the firing-rate distributions associated with the left-choice

573   and right-choice trial types (i.e., FR$_{LEFT}$ or FR$_{RIGHT}$) (**Figure 8A**). The RDI between the

574   visual scenes within the same response type (e.g., zebra stripes and bamboo scenes for the

575   left-choice trial type) (RDI$_{SCN}$) was obtained by calculating the difference in the firing-rate

576   distributions associated with those scenes (with the larger RDI taken between RDI$_{SCN-L}$ and

577   RDI$_{SCN-R}$) (**Figure 8B**). We found no significant difference between the CA1 and subiculum

578   with respect to both RDI$_{CHOICE}$ ($Z = 1.60$, $P = 0.11$, Wilcoxon rank-sum test) (**Figure 8C**)

579   and RDI$_{SCN}$ ($Z = 0.19$, $P = 0.85$) (**Figure 8D**). In addition, no significant difference was found

580   in both RDI measures between the classes of units with single fields and multiple fields in the

581   subiculum (RDI$_{CHOICE}$: $Z = 0.07$, $P = 0.95$; RDI$_{SCN}$: $Z = 0.19$, $P = 0.85$; Wilcoxon rank-sum

582   test). We also tested the possibility that the units recorded from the tetrodes located at the

583   transition zone between the CA1 and subiculum (i.e., SUB/CA1) affected the RDI

584   distributions. However, we found no significant difference between the CA1 and subiculum

585   when running the same statistical tests after removing the units recorded from the SUB/CA1

586   (RDI$_{CHOICE}$: $Z = 0.41$, $P = 0.68$; RDI$_{SCN}$: $Z = 0.32$, $P = 0.75$; Wilcoxon rank-sum test). These

587   findings strongly suggest that task-relevant information (i.e., scene and choice response) is

588   represented robustly in both the CA1 and subiculum when rats perform the VSM task using

589   highly familiar visual scenes.

590

591

592 **In the VSM task, performance was affected by the amount of noise in visual scenes**

593 Prior studies showed that hippocampal neurons systematically respond to the modification

594 made to the familiar environment (Marr, 1971; O'Reilly and McClelland, 1994; Lee et al.,

595 2004; Leutgeb et al., 2004; Ahn and Lee, 2014), but it is relatively unknown whether neurons

596 in the subiculum exhibit similar functional properties. Therefore, after observing the similar

597 neural firing characteristics between the two areas in the VSM task as described above, we

598 then tested whether the neural firing patterns might be dissociated between the CA1 and

599 subiculum if familiar scenes were altered to varying degrees. Specifically, we applied

600 different amounts of Gaussian blur (0% for No-Blur, 30% for Lo-Blur, and 50% for Hi-Blur

601 stimuli) to the original scenes (**Figure 1C**). Only two scenes were used in the blurred version

602 of the task to balance the reduction of the combinatorial complexity of conditions (scene

603 × blur level) with the adequate sampling of neural activity. When the recording session

604 began, the rat first finished 20 trials with the original visual scenes (STD block). Then, from

605 the 21st trial onwards in the session, varying degrees of blurred scenes were presented across

606 trials pseudo-randomly (Blur block). Importantly, the Blur block contained the No-Blur

607 stimuli that were physically identical with the stimuli used in the STD block.

608 When rats performed the blurred task, performance was significantly affected by the

609 different amount of noise ($F_{(3, 15)} = 27.6$, $P < 0.0001$, one-way repeated-measures ANOVA)

610 (**Figure 1D**). This effect largely came from the significant difference in performance between

611 the Hi-Blur and other Blur conditions (P-values < 0.005 for Bonferroni-corrected paired t-

612 tests between Hi-Blur and other Blur conditions; corrected $\alpha = 0.016$), but not from the

613 performance difference between the Lo-Blur and No-Blur conditions ($P = 0.037$ for

614 Bonferroni-corrected paired t-tests between No-Blur and Lo-Blur conditions; $\alpha = 0.016$).

615 However, despite the decrease in performance in the Hi-Blur condition, it is important to note

616 that rats still performed correctly in more than 70% for Hi-Blur trials, which was significantly

617 higher than chance ($t_{(5)} = 6.55$, $P = 0.001$, one-sample t-test). This nonlinear decrease in

618 performance across different blur levels in response to the linear modifications in physical

619 stimuli suggests that the decrease in performance may not be simply driven by changes at

620 sensory-perceptual levels.

621

622

Shift in task demand induced dramatic changes in neural activity in some cells in the

CA1, but not in the subiculum

In the blurred VSM task, we frequently observed that some CA1 units either gained or lost their firing fields immediately after the STD block as the Blur block began. This may not be attributable merely to the changes in stimuli because such radical rate remapping occurred even when the stimuli were physically identical (i.e., No-Blur condition) with those used during the original task (**Figure 9A**). Such rate-remapping patterns were observed less frequently in the subiculum (**Figure 9B**). We excluded the possibility of unstable recording across trials as a source of such regional differences because analyzing only those cells whose spiking activities were identified in both pre-sleep and post-sleep sessions (based on waveforms and cluster configurations in peak planes during unit isolation) also led to the same observations. Compared to the subiculum, the CA1 thus appeared to switch to a different mode of operation as the task demand shifted from recognizing highly familiar visual scenes to processing altered scenes ($Z = 3.47$, $P = 0.0005$; Wilcoxon rank-sum test) (**Figure 9C**). Furthermore, the proportion of cells showing a significant difference in firing rate between STD and No-Blur conditions (based on Wilcoxon rank-sum test) was larger in the CA1 than in the subiculum ($\chi^2_{(1)} = 7.479$, $P = 0.0062$, Chi-square test) (**Figure 9D**).

Overall, our findings suggest that the CA1 responds sensitively to changes in task demand, but the subiculum does not. Furthermore, when comparing the strength of correlation using the autocorrelation matrix of the population ERMs constructed from the single-field units recorded in the blurred VSM task, the subiculum showed significantly higher correlation than the CA1 in the task-congruent regions ($Z = 4.56$, $P < 0.0001$, Wilcoxon rank-sum test), but lower correlation in the task-incongruent regions ($Z = 5.23$, $P < 0.0001$, Wilcoxon rank-sum test). These findings collectively suggest that neurons in the subiculum may not change their firing patterns significantly as long as the overall structure of the task, or schema, remains the same (e.g., between the standard and blur versions of the VSM task).

Neural firing was modulated in the CA1, but not in the subiculum, by the amount of noise in visual scenes

22

653   To test whether differential rate remapping occurred in response to blurred scenes between

654   the CA1 and subiculum, we calculated RDI$_{SCN-C}$ (similar to the RDI$_{SCN}$ or RDI$_{CHOICE}$ but

655   scene and choice variables were not discriminable in the blurred VSM task due to the

656   reduction in the number of visual scenes) between different scenes for each blur level. We

657   observed that the difference in the firing rates associated with different scene conditions

658   decreased as the amount of blur increased especially in Hi-Blur condition in the CA1 (**Figure**

659   **10A**), whereas no such blur-related firing modulation was noticeable in the subiculum

660   (**Figure 10B**).

661   At the neural population level, the RDI$_{SCN-C}$ was significantly different across blur

662   conditions in the CA1 ($\chi^2_{(2)} = 7.05$, $P = 0.0294$, Kruskal-Wallis test) (**Figure 10C**).

663   Specifically, the RDI$_{SCN-C}$ of CA1 units in the Hi-Blur condition was significantly lower than

664   that in the No-Blur condition ($Z = 2.72$, $P = 0.0066$, Wilcoxon rank-sum test with Bonferroni

665   correction; corrected $\alpha = 0.016$), which may underlie the significant drop in behavioral

666   performance (see **Figure 1D**). Similar results were not found in the subiculum ($\chi^2_{(2)} = 3.08$,

667    $P = 0.21$, Kruskal-Wallis test). Furthermore, the RDI$_{SCN-C}$ calculated in the CA1 neural

668   population (after combining the No- and Lo-Blur conditions; Hi-Blur condition was excluded

669   because RDI$_{SCN-C}$ in that condition was expected to be low due to poor behavioral

670   performance) was significantly larger than that calculated in the subiculum ($Z = 2.36$, $P =$

671   0.0184, Wilcoxon rank-sum test) (**Figure 10D**).

672   These findings suggest that even when the noise level is low (Lo-Blur) or none (No-

673   Blur), the shift in task demand may induce a greater rate remapping in the CA1 than in the

674   subiculum. The results thus imply that processing an altered (or ambiguous) context is

675   perhaps the unique computational characteristics of the hippocampus (Marr, 1971; O'Reilly

676   and McClelland, 1994; Treves and Rolls, 1994; Kesner et al., 2000; Lee et al., 2004; Leutgeb

677   et al., 2004; Ahn and Lee, 2014), not shared even with its immediate downstream structure.

678

679   **Rats relied more on visual patterns than on local features of the scenes in the VSM task**

680   It is possible that rats could solve the VSM task in the current study using only local features

681   of the visual scenes. We tested this possibility using a separate group of rats (male Long-

682   Evans, n = 10). Specifically, after being trained to criterion in the VSM task, rats were tested

683   with masked scenes in some trials within a session (intermixed with non-masked, original

684   scene-based trials) (**Figure 11A**). Rats were able to see the overall visual patterns through

23

685   regularly spaced viewing holes in the masked scenes. However, focusing on fixed local

686   features should be difficult in the masked trials because a pair of masking patterns (either pair

687   1 or pair 2 used in a given session) covered different portions of the original scene. In

688   addition, two masking patterns with different sizes of viewing holes (mask pattern 1 and 2 in

689   **Figure 11A**) were intermixed within a testing session. In this control experiment, the average

690   performance levels of rats in the masked trials dropped from the performance level in

691   unmasked trials (original vs. mask pattern 1, $Z = 2.7$, $P < 0.01$; original vs. mask pattern 2,

692    $Z=2.66$, $P < 0.01$; mask pattern 1 vs. pattern 2, $Z = 1.44$, $P = 0.15$; Wilcoxon signed-rank

693   test) (**Figure 11B**), understandably as the scenes were not as clearly discernible in the

694   masked trials as in unmasked conditions. However, it is important to note that performance in

695   masked trials remained well above chance level (50%) (*P*-values < 0.01, Wilcoxon signed-

696   rank test), suggesting that rats used the overall visual pattern in the scene as a cue instead of

697   particular local features.

698

699

700   **Discussion**

701

702   In the current study, we have reported some critical differences in neural firing correlates

703   between the CA1 and subiculum. Specifically, when examined at the population level, the

704   neurons with single fields in the subiculum appear to cover the critical epochs of the task in a

705   schematic (or categorical) manner, as opposed to more specific location-bound fields in the

706   hippocampus. Despite these differences, neurons in both CA1 and subiculum showed similar

707   amounts of rate remapping between different scenes when rats were tested with highly

708   familiar scenes. However, neurons in the CA1 responded more sensitively than subicular

709   cells as soon as the rat detected changes in the environment. That is, some cells in the CA1

710   radically changed their firing rates as the Blur block started by turning on or off their spiking

711   activity, which occurred significantly less in the subiculum. Second, the amounts of rate

712   remapping between different scenes decreased in the CA1 according to the level of visual

713   noise, whereas no systematic relationship could be found in the subiculum.

714   Prior studies also reported the relatively broad fields in the subiculum (Barnes et al.,

715   1990; Sharp and Green, 1994), but their functional significance has been unclear. Our study

24

716   implies that task-related information represented by the focal fields in the CA1 may be

717   packaged in the subiculum into more schematic firing fields matching the critical epochs

718   (e.g., pre- and post-choice periods). The fact that those broadly tuned cells in the subiculum

719   conveyed scene and choice information as robustly as CA1 cells suggest that the schematic

720   firing patterns in the subiculum may not simply stem from poor spatial firing properties. Such

721   interpretations are also supported by the similarity within the same epoch as well as the

722   orthogonality between different epochs in the task, both simultaneously observed in the

723   neuronal population in the subiculum. Theoretically, it may not be necessary for an action

724   system downstream of the hippocampus to know where in the maze a certain scene was

725   experienced with the greatest precision to determine its final action because a background

726   scene is supposed to remain unchanged in a certain area in the environment. According to this

727   scenario, the task epoch-based chunking in the subiculum might be a more practical way of

728   processing information in the downstream regions (especially for action systems) of the

729   hippocampus. The hippocampus may need to monitor contextual information with finer

730   resolutions in space compared to other areas because a novel significant event may occur at

731   any point in time and space (Knight, 1996; Vinogradova, 2001). This speculation may be

732   connected to the phenomenon that subicular cells fired similarly when the rat experienced

733   two adjacent chambers of different shapes (Sharp, 1997) although CA1 neurons tended to

734   remap in those situations.

735   How does such a broadly tuned field arise in the subiculum when its immediate

736   upstream structure exhibits spatially focal fields? One possibility is that efferents of multiple

737   cells in the CA1 may converge onto a single neuron in the subiculum (O'Mara et al., 2009). If

738   multiple afferent cells in CA1 have adjacent or partially overlapping fields, it may result in a

739   broad single field in the receiving subicular neuron. Likewise, a subicular neuron may exhibit

740   multiple fields if its afferent cells have non-overlapping fields. Another possibility is that the

741   broad subicular fields may be driven largely by the upstream neocortical regions (Agster and

742   Burwell, 2013). For example, the firing fields of neurons in the perirhinal cortex tend to cover

743   a large segment of the environment (Bos et al., 2017). However, the range of the coverage of

744   the perirhinal fields appears to be much broader (e.g., an entire left arm of a modified T-

745   maze) than those observed in the subiculum in the current task. We also showed that the

746   schematic coding could not be simply generated by large subicular fields in our task,

747   emphasizing the importance of some structured organization of the population representations

748   reflecting task demands. Finally, the so-called axis-tuned cells in the subiculum (Olson et al.,

25

749   2017) might underlie our findings because the pre-choice and post-choice epochs in our task

750   roughly correspond to the vertical and horizontal axes of the T-maze, respectively. However,,

751   it is unlikely that the phenomenon reported here was mainly driven by axis-tuned cells in the

752   subiculum. This is because there were approximately 8% of cells in the subiculum that were

753   identified as axis-tuned cells according to the previous study (Olson et al., 2017), whereas

754   over 40% of recorded units in the subiculum showed broad single fields in our study. Also,

755   the single-field units in our study showed rate remapping according to the task-relevant

756   information to the similar extent compared to CA1 cells, suggesting that the subicular cells

757   may represent more complex task-specific components than a simple spatial component.

758   To our knowledge, the scene- and choice-dependent rate remapping of the subiculum

759   in a memory task have never been reported. Together with the rate remapping previously

760   observed in the CA1 and dorsomedial striatum in the VSM task (Delcasso et al., 2014), the

761   subicular rate remapping reported here may support the idea that scene-dependent rate

762   remapping may not be a unique code of the hippocampus. Instead, rate remapping may be a

763   general code used across different areas. Subicular neuronal firing carried similar amounts of

764   scene and choice signals compared to the hippocampal firing when the rat performed the

765   overly trained task with the same scenes. However, introducing a novel task demand by

766   intermixing blurred stimuli with the original ones altered the firing patterns of the CA1

767   dynamically to reflect the physical changes in the scenes. The subicular network did not show

768   such properties. These results suggest that novel components in both task demand and visual

769   scene may be detected and processed primarily by the hippocampus, and the subiculum may

770   not be functionally active until novelty subsides and the stimuli became familiar (Roy et al.,

771   2017). Although the underlying mechanisms are unknown, our results indicate that the

772   information processing between the hippocampus and subiculum is under dynamic control

773   depending on task demands.

774   The lack of significant functional differences along the proximo-distal axis in our

775   study may be attributable simply to the inadequate sampling of neural activity especially in

776   the distal area and the most proximal portion of the CA1. Another possibility is that the

777   nature of the functional distinction between the proximal and distal portions of the region

778   might be more complex in a goal-directed, complex memory task compared to random

779   foraging situations (Henriksen et al., 2010) and simple behavioral paradigms (Cembrowski et

780   al., 2018). For example, the perirhinal and postrhinal cortices, the upstream areas of the

781   lateral and medial entorhinal cortices, respectively, also project directly to the CA1 and

782 subiculum (Kosel et al., 1983; Naber et al., 1999; Witter, 2006). In our recent studies, we

783 have shown that the functional distinctions at the perirhinal-postrhinal cortical level were less

784 clear than at the entorhinal cortical level in the scene-dependent memory tasks although both

785 perirhinal and postrhinal cortices play some significant roles in the tasks (Park et al., 2017;

786 Yoo and Lee, 2017). It is possible that there might be some dynamic interactions among the

787 retrohippocampal cortices through the hippocampal formation when the rat is engaged in a

788 goal-directed, complex memory task and a more sophisticated behavioral task is needed to

789 dissociate these regions physiologically.

790   The schematic firing patterns of subicular cells in the current study might be

791 contrasted with the diverse firing patterns of subicular neurons reported in prior studies

792 (Brotons et al., 2017). One of the major differences is that we used a mnemonic task in the

793 current study, whereas most prior studies recorded neural activity in a foraging paradigm

794 using an open field. It is well known that goal-directed, structured information processing

795 results in different firing properties in the hippocampal formation, compared to random

796 foraging situations. For example, place cells in the hippocampus and subiculum tend to

797 remap on a linear track as the rat passes the same locations from different directions to reach

798 different goal locations (as opposed to the animal randomly foraging in an open field)

799 (Barnes et al., 1990; McNaughton et al., 1983; Geva-Sagiv et al., 2016). Also, changes in task

800 demand such as rules and memory load alter the firing characteristics of hippocampal cells in

801 goal-directed tasks (Markus et al., 1995; Hallock and Griffin, 2013). Although we did not

802 record subicular cells in a foraging paradigm, it is possible that one might not be able to

803 observe the schematic firing patterns reported in the current study if an animal randomly

804 forages in an open field. This conjecture may be supported by the anatomical connections of

805 the subiculum, showing independent and rich connections with various regions other than the

806 hippocampus (e.g., the amygdala, nucleus accumbens, retrosplenial cortex, prefrontal cortex,

807 and retrohippocampal cortices) (Agster and Burwell, 2013; Cembrowski et al., 2018) that

808 may play key roles in goal-directed memory tasks. Given a paucity of subicular recording

809 studies using mnemonic tasks (Hampson and Deadwyler, 2003), our results may add valuable

810 information to understanding the functional significance of subicular firing patterns in a

811 memory task.

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941

942 **Figure Legends**

943

944 **Figure 1. Behavioral paradigms and performance.** (**A**) The standard version of VSM task.

945 Scenes (Z: zebra stripes, B: bamboo, P: pebbles, M: mountains) used as visual contexts. The

946 rat chose an arm associated with the visual scene to obtain a piece of cereal in a food well.

947 RW: reward, S: start box. (**B**) Performance for each scene stimulus (color-coded for

948 individual rats). Performance exceed criterion (dashed line, 75%) for all scenes. (**C**) Scene

949 stimuli used in the blurred version of the VSM task and the correct responses associated with

950 the stimuli. Only Z and P were used in the blurred version. The original stimuli (STD or No-

951 Blur) were blurred by applying a Gaussian smoothing either by 30% (Lo-Blur) or 50% (Hi-

952 Blur). (**D**) Behavioral performance in the blurred version of the VSM task. Performance

953 (black line) significantly dropped only in the Hi-Blur condition compared to all other

954 conditions. However, the pixel-to-pixel correlation coefficient between original and blurred

955 scenes decreased almost linearly as the amount of blur increased (red line for Z and blue line

956 for P). Mean ± S.E.M. **$P < 0.01$.

957

958 **Figure 2. Simultaneous recording of single units from the CA1 and subiculum.** (**A**)

959 Proportional distribution of cells recorded in the CA1 (blue) and subiculum (SUB; red) along

960 the proximo-distal axis (top) and a flat map showing tetrode positions in the CA1 and

961 subiculum (bottom). The intermediate transition zone (SUB/CA1) is colored in white.

962 Numbers on the left of the flat map indicate relative positions (mm) from bregma. Colored-

963 dots represent tetrode positions for individual rats. A: anterior, P: posterior, M: medial, L:

964 lateral. (**B**) Nissl-stained photomicrographs of the tissue sections that contained the tetrode

965 trajectories marked by the arrows in (A). (**C**) Basic firing properties of single units in the

966 CA1 and subiculum.

967

968 **Figure 3. Event-related firing patterns in the CA1 and subiculum.** (**A**) Major events in

969 the VSM task. The opening of the start box door (S), turning to the left or right arm at the

970 choice point (C), and reaching the reward location (R) were defined as three major events.

971 Three sensor-crossing points in the stem and bisecting point of each arm were minor events.

972 The arrow denotes the running direction. (**B**) Event rate map (ERM). The raster plot of a

973 single unit is used to as an example to illustrate how spiking activities were grouped into

974 discrete event epochs to result in the ERM. (**C**) Examples of the event rate maps (ERM) and

975 spatial rate maps (SRM) of cells in the CA1 and subiculum. The epoch between the opening

976 of the start box and track entrance was not represented in the spatial rate map because the

977 associated position data were not recorded in the start box in our experimental settings,

978 whereas the event rate map could represent neural activity in the entire task period (including

979 the neural activity inside the start box). Although the information-organizing schemes were

980 different between the event rate map (time) and spatial rate map (location), both formats were

981 very similar because time and location were highly correlated in our task on the maze. (**D**)

982 Distribution of the Pearson correlation coefficients between the event rate maps and spatial

983 rate maps (excluding the start box) of individual neurons of the CA1 (left) and subiculum

984 (right). Two type of maps were highly correlated in the most of cells, and only 6 out of 325

985 cells (n = 1/109 in CA1, n = 5/216 in subiculum) showed no correlation between two maps.

986

987 **Figure 4. Types of firing fields in the CA1 and subiculum.** (**A** and **B**) Representative

988 ERMs in the CA1 (A) and subiculum (B). Numbers indicate the maximal firing rates. The

989 color bar denotes the color scale for firing rate (max: maximal firing rate). (**C**) The

990 proportion of single- and multiple-field types in the CA1 and subiculum. (**D**) Comparison of

991 the field sizes of the units with single fields and multiple fields in the CA1 and subiculum.

992 Inset: Same data presented as bar graphs. Median ± 95% confidence interval/2. ** $P < 0.01$,

993 *** $P < 0.001$. (**E**) Histograms to compare the proximo-distal distributions of single-field

994 units with multiple-field units in the subiculum. Overlapping areas between single- and

995 multiple-field distributions are colored in white. Note the presence of more multiple-field

996 units in the distal subiculum (green areas) and more single-field units in the proximal

997 subiculum (red areas).

998

999 **Figure 5. Schematic firing patterns of the neural populations in the subiculum, but not**

1000 **in the CA1.** (**A**) Population ERMs for the CA1 and subiculum. Individual ERMs were

1001 aligned according to their maximal firing locations along the event dimension (S-C-R). The

1002 white dotted line denotes the boundary between the pre-choice (pre-C: S to C) and post-

1003 choice (post-C: C to R) periods. (**B**) Autocorrelation matrix showing the cross-correlations

1004 between the same population ERMs to reveal positively correlated (warm colors) and anti-

33

1005   correlated (cool colors) areas in the population ERM. Black dashed line: choice point. (**C**)

1006   Task-congruent (TC, orange triangles) and task-incongruent (TI, blue rectangle) areas in the

1007   autocorrelation matrix (only shown in the lower half of the matrix to avoid duplicate

1008   information). (**D** and **E**) Comparison of mean correlation coefficients between the CA1 and

1009   subiculum in the task-congruent area (D) and task-incongruent area (E). ***$P < 0.001$. (**F**)

1010   Representative examples of the population ERMs containing the randomly shifted ERMs for

1011   individual cells in the CA1 and subiculum. The locations of ERMs were shuffled and sorted

1012   by their peak firing locations. Note that the characteristic schematic firing across the choice

1013   point observed in the original population ERM for the subiculum disappeared. (**G**) Averaged

1014   autocorrelation matrix using the shifted ERMs. The correlational pattern made of the shifted

1015   ERMs in the subiculum became similar to that of the CA1. (**H**) Representative examples of

1016   cells showing speed correlation in the CA1 (left) and subiculum (right). The ERMs of the

1017   speed-correlated cells were similar to the speed maps in the corresponding session (color

1018   maps, top; numbers indicate maximal speed and firing rate), and there was a significant

1019   correlation between the in-field firing rates and their associated running speeds in individual

1020   trials (scatter plots, bottom).

1021

1022   **Figure 6. Illustration of the differential coding schemes between the hippocampus and**

1023   **subiculum.** Location-specific firing patterns of CA1 cells are translated (by chunking) into

1024   schematic representations in the subiculum. Overlapping fields in different colors illustrate

1025   the scene-dependent rate remapping with each field associated with one of the visual scenes

1026   in the task.

1027

1028   **Figure 7. Task-dependent rate remapping in the CA1 and subiculum.** (**A** and **B**)

1029   Representative ERMs of CA1 (A) and subicular (B) cells, associated with four scenes (Z, B,

1030   P, and M). Cells are sub-categorized into nonspecific, choice-specific and scene-specific

1031   units. Scene and associated spatial choice are labeled on the left side of each ERM. The

1032   number at the end of the ERM of each cell denotes the maximum firing rate.

1033

1034   **Figure 8. Comparison of rate remapping between the CA1 and subiculum.** (**A** and **B**)

1035   Illustration of the procedures for calculating the rate difference index (RDI). Each panel

34

1036   consists of the ERMs associated with different task-relevant information (top) and line graphs

1037   that compare the firing rates between different scene conditions along the event axis

1038   (bottom). (**A**) Rate difference index for choice (RDI$_{CHOICE}$). Scenes associated with the same

1039   choice arm were combined to measure the field's firing rate for each side (i.e., FR$_{LEFT}$ and

1040   FR$_{RIGHT}$). RDI$_{CHOICE}$ is the difference between the firing rates associated with the left and

1041   right choices. (**B**) Rate difference index for the scene (RDI$_{SCN}$). RDI$_{SCN-L}$ and RDI$_{SCN-R}$ are

1042   RDI values computed for different scenes that share the common choice arm, and the larger

1043   of the two was taken as RDI$_{SCN}$ of the unit. (**C** and **D**) Cumulative distributions of RDI$_{CHOICE}$

1044   (**C**) and RDI$_{SCN}$ (**D**). RDI$_{CHOICE}$ was not significantly different between the CA1 and

1045   subiculum, and the same was the case for RDI$_{SCN}$.

1046

1047   **Figure 9. Dramatic neuronal remapping in the CA1 upon task switching, but not in the**

1048   **subiculum.** (**A** and **B**) Comparison of spiking activities between STD and No-Blur

1049   conditions in the CA1 (A) and subiculum (B). Spiking activity was turned on (cell 1) or off

1050   (cell 2) as task demand shifted from processing original scenes to processing various scenes

1051   including the blurred ones from the 21st trial (only the spiking data from the No-Blur trials are

1052   shown here). Such radical remapping was less frequently observed in the subiculum. Neural

1053   spikes are aligned to the start-box door opening event (zero). The ERMs for STD and No-

1054   Blur blocks are shown. For each cell, the average waveforms from four channels of the

1055   tetrode recorded from pre-sleep to post-sleep session are shown. Scale bar = 50 μV. (**C**)

1056   Comparison of the amounts of rate modulation between STD and No-Blur conditions in the

1057   CA1 and subiculum. ***$P < 0.001$. (**D**) The proportion of cells that underwent significant

1058   rate modulations between STD and No-Blur. The numbers of cells are given in the

1059   parentheses. *$P < 0.05$.

1060

1061   **Figure 10. Blur level-dependent neural changes in the CA1, but not in the subiculum.** (**A**

1062   and **B**) Representative ERMs of CA1 (A) and subiculum (B). The amount of rate modulation

1063   (RDI$_{SCN-C}$) between different scene/choice decreased in CA1 units as the level of noise (i.e.,

1064   blur) in the scene stimuli increased, whereas the patterns of rate modulation in the subiculum

1065   were not correlated with the blur levels of the stimuli. The numbers below the ERM indicate

1066   the maximal firing rates. (**C**) Cumulative distributions of RDI$_{SCN-C}$ for different blur

1067   conditions in the CA1 and subiculum. Note the gradual shift toward lower RDI$_{SCN-C}$ values as

1068   the blur level increased in the CA1, but not in the subiculum. Inset: the same data shown as

1069   bar graphs. Median ± 95% confidence interval/2. **$P < 0.01$. (**D**) Comparing $\text{RDI}_{\text{SCN-C}}$

1070   values of No-Blur and Lo-Blur conditions between the CA1 and subiculum. More units in the

1071   CA1 changed their firing rates as a function of visual scenes than in the subiculum.

1072   *$P < 0.05$.

1073

1074   **Figure 11. VSM task with masked stimuli.** (**A**) Scene stimuli used in the masking

1075   experimental session. In each session, one of the two pairs was chosen from mask pattern 1

1076   and 2, and those individual masking patterns were pseudo-randomly presented in an

1077   intermixed fashion throughout the session with the original scene. (**B**) Box plots showing

1078   rat's performance in the masking session. For each masking pattern with either larger or

1079   small viewing holes, mean performance of a rat is plotted as a dot. Dashed line: chance

1080   performance level. **$P < 0.01$.

A

Z

P

B

M

RW

RW

Left
choice

Right
choice

S

S

B

% Correct

100
90
80
70
60
50

Z   B   P   M

Scene

● rat1
● rat2
● rat3
● rat4
● rat5
● rat6
● rat7

C

Blur level

Hi
Lo
No
(=STD)

Z

P

RW

RW

Left
choice

Right
choice

S

S

D

% Correct

100
90
80
70
60
50

Pixel-to-pixel
Correlation (R)

1.0
0.8
0.6
0.4

T1~20

T21~

STD   No   Lo   Hi

Blur

**

**

**

—○— Performance
—○— Correlation of Z
—○— Correlation of P

A

B

C

A

R Reward
Middle of arm
C Choice
Optic sensor 3
Optic sensor 2
Optic sensor 1
S Start
(Stimulus onset)

B

S   C   R

Trial

Time

C

CA1

Track entrance

S   C   R

cell 1 { ERM
         SRM

cell 2 { ERM
         SRM

cell 3 { ERM
         SRM

SUB

S   C   R

cell 4 { ERM
         SRM

cell 5 { ERM
         SRM

cell 6 { ERM
         SRM

D

CA1

Proportion

0.3
0.2
0.1
0.0

-0.2   0   0.2 0.4 0.6 0.8   1
Correlation coefficient

SUB

Proportion

0.3
0.2
0.1
0.0

-0.2   0   0.2 0.4 0.6 0.8   1
Correlation coefficient

☐ Significant correlation   ■ Non-significant correlation

A CA1

B SUB

Single field (SF)

Multiple fields (MF)

SF

MF

C

CA1   SUB
***

1%
15%
84%

47%   42%
11%

SF   MF   Event-unrelated

D

Proportion

Field size

Field size

CA1 SF
SUB SF
SUB MF

E

Proportion

Distal ←→ Proximal

SF > MF
MF > SF

A CA1 SUB

B

C

D

E

F Shifted CA1 Shifted SUB

G

H CA1 SUB

CA1

SUB

Spatial
(location-bound)

Schematic
(task demand-bound)

Z   **B**   **P**   **M**

A

cell 1   cell 2   cell 3   max

Nonspecific

Left { Z
       B

Right { P
        M   21.8   29.5   28.1   0

Choice

              cell 4   cell 5   cell 6

Left { Z
       B

Right { P
        M   7.3   10.2   15.0

(Event-specific)

              cell 7   cell 8   cell 9

Scene

Left { Z
       B

Right { P
        M   9.1   12.6   27.6

B

              cell 10   cell 11   cell 12

Nonspecific

Left { Z
       B

Right { P
        M   18.8   49.1   17.7

Choice

              cell 13   cell 14   cell 15

Left { Z
       B

Right { P
        M   4.4   17.5   19.5

(Event-specific)

              cell 16   cell 17   cell 18

Scene

Left { Z
       B

Right { P
        M   4.4   11.7   4.0

A

CA1

S ● ● ● C ● R

Z
B
Left

P
M
Right

} RDI$_{CHOICE}$

Firing rate

12
8
4
0

Z
B
P
M

SUB

S ● ● ● C ● R

Z
B
Left

P
M
Right

} RDI$_{CHOICE}$

Firing rate

8
4
0

Z
B
P
M

$$RDI_{CHOICE} = \left| \frac{mean(FR_{LEFT}) - mean(FR_{RIGHT})}{std(FR_{LEFT}, FR_{RIGHT})} \right|$$

B

CA1

S ● ● ● C ● R

Z
B
} RDI$_{SCN-L}$

Firing rate

30
15
0

Z
B

P
M
} RDI$_{SCN-R}$

Firing rate

30
15
0

P
M

SUB

S ● ● ● C ● R

Z
B
} RDI$_{SCN-L}$

Firing rate

6
4
2
0

Z
B

P
M
} RDI$_{SCN-R}$

Firing rate

6
4
2
0

P
M

$$RDI_{SCN} = max(RDI_{SCN-L}, RDI_{SCN-R})$$

C

Proportion

1.0
0.8
0.6
0.4
0.2
0

n.s.

CA1
SUB

0   0.4   0.8   1.2   1.6
RDI$_{CHOICE}$

D

Proportion

1.0
0.8
0.6
0.4
0.2
0

n.s.

CA1
SUB

0   0.4   0.8   1.2
RDI$_{SCN}$

A

cell 1

trial

1

49

-1   0   2.5 (s)

STD

No-Blur

pre-sleep   behavior   post-sleep

cell 2

trial

1

40

-1   0   2.5

STD

No-Blur

pre-sleep   behavior   post-sleep

B

cell 3

trial

1

49

-1   0   2.5

STD

No-Blur

pre-sleep   behavior   post-sleep

cell 4

trial

1

51

-1   0   2.5

STD

No-Blur

pre-sleep   behavior   post-sleep

C

Proportion

1.0
0.8
0.6
0.4
0.2
0

***

CA1
SUB

0   1   2   3   4   5

RDI
(between STD and No-Blur)

D

*

CA1   SUB

25.0%
(7)

75.0%
(21)

46.1%
(53)

53.9%
(62)

Significant rate modulation
between STD and No-Blur

A

Blur level
Scene
CA1
RDI_{SCN-C}
0   0.6

cell 1
No Z P
Lo Z P
Hi Z P
11.6

0   0.5

cell 2
No Z P
Lo Z P
Hi Z P
14.3

0   1.2

cell 3
No Z P
Lo Z P
Hi Z P
18.1

B

Blur level
Scene
SUB
RDI_{SCN-C}
0   0.5

cell 4
No Z P
Lo Z P
Hi Z P
27.8

0   0.5

cell 5
No Z P
Lo Z P
Hi Z P
26.2

0   0.5

cell 6
No Z P
Lo Z P
Hi Z P
33.8

C

CA1

SUB

Proportion

RDI_{SCN-C}

RDI_{SCN-C}

1.0
0.8
0.6
0.4
0.2
0
0   1   2

0.6

**

n.s.

Blur No Lo Hi

D

Proportion

1.0
0.8
0.6
0.4
0.2
0
0   1   2

*

CA1
SUB

RDI_{SCN-C}
(No-Blur & Lo-Blur)

Original scene

A

Mask pattern 1
(larger viewing area)

Mask pattern 2
(smaller viewing area)

Pair 1

Pair 2

B