

## Place cells of aged rats in two visually identical compartments

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Received 26 April 2004; received in revised form 11 August 2004; accepted 15 September 2004

### Abstract

Aged rats perform poorly on spatial learning tasks, a cognitive impairment which has been linked to the failure of hippocampal networks to fully encode changes in the external environment [Barnes CA, Suster MS, Shen J, McNaughton BL. Multistability of cognitive maps in the hippocampus of old rats. *Nature* 1997;388(6639):272–5; Wilson IA, Ikonen S, Gureviciene I, McMahan RW, Gallagher M, Eichenbaum H, et al. Cognitive aging and the hippocampus: how old rats represent new environments. *J Neurosci* 2004;24(15):3870–8]. To examine whether the impairment in hippocampal processing extends to conditions in which self-motion provides the cues for environmental change, we have analyzed spatial firing patterns of hippocampal pyramidal neurons in young and aged rats, as well as in young rats with selective cholinergic lesions, another model of cognitive aging. The rats walked between two visually identical environments, pitting self-motion cues that indicated environmental change against visual inputs that indicated no differences between environments. Our results indicated that place cells in both aged and cholinergic-lesioned rats were equally likely as those of young rats to create new spatial representations in the second compartment. These findings suggest that the hippocampal network of aged rats is able to process changes in internally generated cues without rigidity, but that incomplete processing of external landmark cues may lead to impaired spatial learning.

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**Keywords:** Place cells; Spatial memory; Aging; Hippocampus; Idiothetic; Self-motion; Age-associated cognitive impairment; Medial septum

### 1. Introduction

Many aged humans [22] and animals (for review, see [25]) have diminished spatial memory capacity associated with a deterioration of hippocampal connectivity and plasticity (for review see [9,29]). In order to investigate how information is processed differently in the aged hippocampus than in the young hippocampus at the neuronal level, several researchers have recorded from hippocampal “place cells”, pyramidal neurons in areas CA1 and CA3 that are activated when the rat moves through particular places within an environment [2,24,30,37,39,40]. A major finding of these studies is that hippocampal place cells are less controlled by the visual sur-

roundings in aged rats than in young rats. In aged rats, place cells are likely to maintain the same spatial firing pattern across two different environments, a situation in which place cells of young rats typically change their spatial representation ([38–40] as well as [24]). Further, the rigidity of place cells in aged rats correlates strongly with the extent of spatial memory impairment [40].

Two hypotheses have been offered to account for impaired spatial information processing in the aged rat hippocampus. At the behavioral level, aged rats have an increased dependence upon idiothetic (self-motion) cues, as compared to the influence of external visual cues [1]. This may extend to hippocampal processing. When young rats are moved from a familiar to a novel environment, their place cells are only briefly controlled by idiothetic cues and then rapidly come under the control of the new visual cues [20,41]. By contrast,

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place cells of aged rats are delayed in making this switch [30] and, even with prolonged exposure to the new environment, are inconsistently controlled by the visual landmarks [39].

Alternatively, hippocampal networks may have a propensity to rigidly maintain a spatial representation when cues are changed. Several studies have reported weakened cholinergic modulation [5,11,23,35] and diminished entorhinal cortical input [10,27,34] to the aging hippocampus. These changes may shift the balance of information flow away from the normally strong new inputs from the entorhinal cortex [12] and towards pattern completion of previously learned associations by the CA3 auto-associative network, resulting in a resistance to change with alterations in cues. Consistent with this view, selective cholinergic lesions of the hippocampus reproduce the phenomenon of rigidity characteristic in hippocampal place cells of aged rats [14,17].

We have addressed these two hypotheses by characterizing the spatial firing patterns of hippocampal cells under conditions in which the idiothetic information indicates environmental change while the visual inputs remain the same. Young and aged rats, as well as young rats with selective cholinergic lesions, explored a small box with distinct visual landmarks. Then they freely walked through a hidden door to a visually identical second compartment. If the influence of self-motion is intact in aged rats, then their place cells should be at least as likely as those of young rats to create new spatial representations, unlike the typical rigidity in their response when environmental cues are altered. On the other hand, if the aged hippocampal network is generally rigid, place cells of aged rats should show greater similarity in spatial representations across the two compartments than those of young rats. Our results indicated that place cells of aged rats were as likely to change representations as those of young rats, suggesting that the aged hippocampal network does not suffer from a general rigidity. Similarly, the spatial representations of rats with selective cholinergic lesions also changed when animals used exclusively internal cues, strengthening the parallels between aging and cholinergic dysfunction in hippocampal processing mechanisms.

## 2. Methods

### 2.1. Subjects and surgery

The subjects were Long–Evans male rats, 12 young intact or sham operated (6–8 months), six young with IgG-saporin lesions of the medial septum and diagonal band of Broca (Ch-X rats, 5–7 months), and 10 aged intact (24–27 months). Young controls were matched with either aged or young cholinergic-lesioned rats. Because aged animals vary in their abilities to learn new spatial information [8], the aged rats and their young counterparts were pre-tested in the water maze test for spatial learning capacity. It has been shown that medial septum cholinergic lesions do not impair spatial water maze learning [3,4] so rats with selective cholinergic

lesions and their matched controls were not tested. The water maze tests and lesion surgeries were done at Johns Hopkins University before the rats were sent to the University of Kuopio for electrophysiological testing. Several days prior to the experiment described here, all rats took part in a battery of place cell experiments already published [14,39,40].

The spatial navigation and visible cue water maze protocol have been reported earlier with these same aged and young rats [40]. Briefly, for the spatial navigation task the rats received three trials per day for 8 consecutive days. The location of the hidden platform remained constant, whereas the starting position for each trial was varied among four perimeter positions. Every sixth trial was a probe trial during which the platform was retracted and unavailable for escape. The probe trials assessed if there was development of a spatial bias in searching for the escape platform. The primary measure, referred to as the learning index, is derived for each rat from the probe trials. The learning index is computed as the average proximity of the rat to the platform over a series of probe trials over the course of training such that low values represent a more rapid and accurate acquisition of a search for the escape platform, while high values indicate poor performance [8]. In order to test visual acuity and swimming ability independent of the ability to process spatial information, each rat was given six cued training trials on the day after completion of the spatial training trials.

The surgical procedures for the cholinergic immunolesions have been reported in detail earlier [3,19]. Briefly, under Nembutal anesthesia (50 mg/kg), 192 IgG saporin (0.5  $\mu\text{g}/\mu\text{l}$ , Chemicon, Temecula, CA) or phosphate-buffered saline was injected at two depths bilaterally at AP +0.45 mm and ML +0.6 mm referenced to Bregma. A total volume of 0.3  $\mu\text{l}$  was infused to the sites at DV  $-7.8$  mm, and a total volume of 0.2  $\mu\text{l}$  was infused into the sites at DV  $-6.2$  mm.

Electrode implantation and recordings were done at the University of Kuopio. Under general anesthesia (pentobarbital and chloral hydrate each 40 mg/kg i.p., supplemented with ketamine 20 mg/kg i.m.) each rat was implanted with two or four movable tetrodes (a bundle of four twisted 30  $\mu\text{m}$  Nichrome wires containing 10% iron) aimed at CA1 of each hemisphere (AP  $-3.3$  mm, ML  $\pm 1.8$  mm, DV  $-2.2$  mm from the dura). In addition, bipolar stimulation electrodes were implanted in the lateral hypothalamus to deliver rewarding brain stimulation (AP  $-0.5$  mm, ML  $\pm 1.6$  mm, DV  $-7.8$  mm from the dura). Further details of the recording techniques are found in [14], and the implant construction and the surgical procedure have been described earlier in Tanila et al. (1997a). All experiments were conducted in accordance with NIH and Council of Europe guidelines and approved by the Institutional Animal Care and Use Committee.

### 2.2. Apparatus

The experimental apparatus and procedures have been reported earlier [36]. After full recovery from the implant surgery, the rats were trained to search for randomly dis-

tributed loci within a brown paste-board cylindrical environment (diameter 70 cm, height 50 cm) where rewarding brain stimulation was delivered. The stimulus current was adjusted to the minimum level that kept each rat constantly moving. During this training period, the recording electrodes were advanced until single hippocampal pyramidal cells were isolated. The recording environment consisted of two rectangular compartments, each with three identical cue cards on the walls (see Fig. 1, length 41 cm, width 34 cm, and height 32 cm). The compartments were joined by a common wall that contained a hidden double-leaf door that could swing to

open a 10 cm wide walkway. The compartments are hereafter referred to as Box A and Box B. Special care was taken to make compartments as visually identical as possible. Whenever the rat was lifted into one of the compartments, the other was covered with a cardboard sheet to prevent the rat from seeing the entire layout.

The compartments were located on a black plastic table (diameter 1.1 m). The table and compartments were surrounded by a floor-to-ceiling circle of black curtain (diameter 2.2 m); the rat remained inside this curtained area for the entirety of each recording session. The compartments were equally illuminated by four incandescent bulbs arranged symmetrically 1.5 m above the center of the table floor. The room was quiet except for the sound of a ventilation fan that created a diffuse background white-noise. These factors all served to limit the orienting cues outside the compartment frame.

### 2.3. Experimental procedures

The place cell recording protocol followed the sequence of trials A1–B2–B3–A4 (see Fig. 1). All recording trials lasted for 5 min. Initially the rat was placed in Box A and allowed 15–25 min to familiarize itself with the novel environment. Place cells were recorded for the last 5 min of this exploration period. The experimenter then quietly opened the hidden door, allowing the rat to walk into Box B. Once the rat had entered, the door was closed and the trial B2 began. After 5 min, the rat was lifted out and placed into a bucket (diameter 40 cm, height 80 cm) suspended above the compartments. There the animal rested for 5 min while the compartment floors were cleaned. The bucket was not spun in order to avoid disorienting the rat. The rat was lifted back into compartment B for trial B3 and then, after the 5 min recording trial, the door was again opened and the rat walked back into Box A for trial A4.

### 2.4. Spatial firing pattern analysis

The recordings were made with Enhanced Discovery software, and cells were isolated off-line by clusters defined with waveform parameters using Autocut software (both from DataWave Technologies, Longmont, CO, USA). Place cells were defined as pyramidal cells (based on the presence of complex spikes and duration of the negative spike more than 300  $\mu$ s) with a place field in at least one of the recording environments. Place fields were defined as a set of at least six adjacent pixels (each pixel was 3.5 cm  $\times$  3.5 cm) with firing rates above 0.5 Hz and two times above the cell's overall mean firing rate. Cells were included in the study if they had clear place fields in at least one recording environment and showed clear amplitude differences between the four-tetrode channels (indicating good isolation). To compare the properties of place cells between groups, analyses were based upon the overall firing rates, which were calculated for periods when the rat was moving at least 2 cm/s. This speed filter minimized contamination of the location-specific fir-

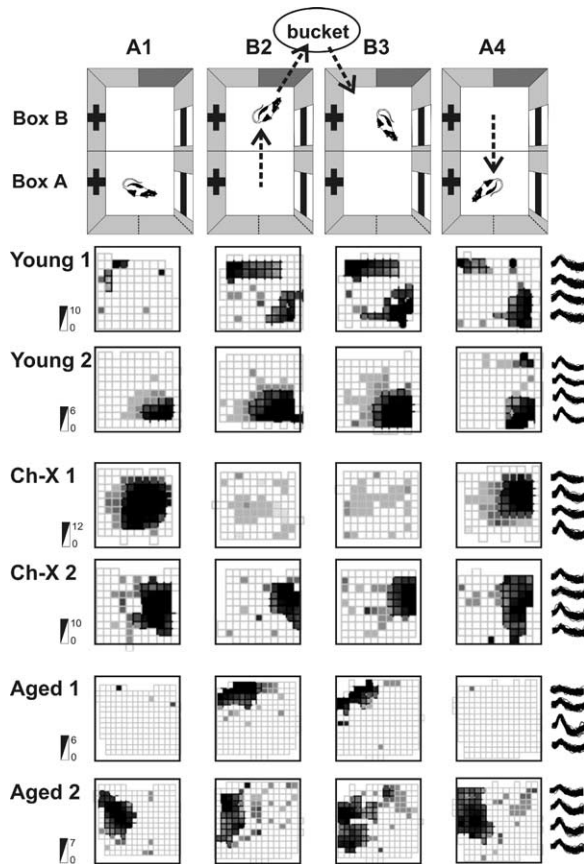


Fig. 1. Spatial representations in visually identical compartments. The top row illustrates the experimental protocol. For details see text. Boxes A and B are separated by a wall with a hidden door. Dashed arrows indicate transitions between the trials: walking from A1 to B2, lifted passively by the experimenter from B2 into a hanging bucket then to B3, and walking from B3 to A4. Each row thereafter depicts the spatial firing patterns of one cell across the experiment. Note that only the explored arena (Box A or B) is shown for each trial. Dark pixels represent high activity as shown by the firing rate scales provided on the left. Example tetra-waveforms of each cell are shown on the right. Cell Young 1 shows different spatial representations in trials A1 and B2. The new representation is maintained into trial A4, demonstrating differences between A1 and A4 spatial representations observed occasionally in young rats. Cell Young 2 shows a spatial representation that did not change across the trials. Cell Ch-X 1 had a low spatial correlation between the A and B compartments, whereas cell Ch-X 2 had a high correlation. Cell Aged 1 was silent in environment A, but active in Box B. Cell Aged 2 had a similar firing pattern on all trials. These two cells were recorded simultaneously from the same rat and thus illustrate the discordant responses observed within an ensemble.

ing with spikes during sharp wave activity (see [6]). We also compared spatial selectivity, calculated by the spatial information content [18,33]. For each trial, the spatial selectivity was calculated only if the mean firing rate of the cell was above 0.1 Hz.

In order to measure the extent to which a spatial representation changed between trials in the different compartments, we quantified the similarity between firing rate maps calculated as pixel-to-pixel cross-correlations. We calculated the cross-correlations only if a place field was evident in at least one of the trials. As a second measure of the neuronal response to the movement across compartments, we calculated the magnitude of firing rate change (independent of direction) between environments, computed as:  $ABS \left[ \frac{(fr1 - fr2)}{\{(fr1 + fr2 + fr3 + fr4)/4\}} \right]$ , such that ABS: absolute value, fr1: firing rate A1, fr2: firing rate B2, fr3: firing rate B3, and fr4: firing rate A4. This measure allowed us to account for cells which were silent in one of the environments, a situation in which spatial correlations cannot be used.

## 2.5. Histology

At the end of the study, the rats were deeply anesthetized and the recording sites were marked by passing anodal current (30  $\mu$ A, 5 s) through the electrodes. The animals were perfused with buffered 4% formalin, and the brains were cut into 50  $\mu$ m sections. The locations of the electrodes tips were confirmed by Prussian blue reaction, as described earlier [37]. The immunotoxin lesions were evaluated by AChE staining of sections taken through the hippocampus (as described in [13]) and by loss of ChAT-positive neurons in the medial septum (as described in [21]).

## 3. Results

### 3.1. Lesion and spatial learning

The IgG-saporin lesion of the medial septum produced substantial loss of cholinergic innervation of the hippocampus. For further details of the histology, see [14]. The aged rats had significantly impaired spatial memory compared to the young rats (learning index scores: aged =  $245 \pm 12$  cm; young =  $187 \pm 11$  cm, mean  $\pm$  S.E.M.;  $t(13) = 0.43$ ,  $P > 0.60$ ). For further details, see [40].

### 3.2. Place cells

We simultaneously recorded multiple hippocampal place cells, which met the criteria (see Section 2;  $n = 2.4 \pm 0.2$ ; mean  $\pm$  S.E.M.) as the rats explored the two visually identical environments. We recorded from the young rats 17 CA1 place cells and 6 CA3 cells, from the medial-septum lesioned rats 7 CA1 cells and 6 CA3 cells, and from the aged rats 19 CA1 cells and 11 CA3 cells. Because there were no differences in any of the measures between hippocampal subfields,

the data from the two hippocampal areas were pooled for each group.

In the individual trials, the spatial firing characteristics of the groups were not significantly different. The firing rates were the same across all groups in all environments (firing rate A1 (for example): young =  $0.89 \pm 0.18$  spikes/s; Ch-X =  $1.8 \pm 0.34$  spikes/s; aged =  $1.22 \pm 0.32$  spikes/s, mean  $\pm$  S.E.M.; one-way ANOVAs all trials  $t(2,24) < 2.5$ ,  $P > 0.10$ ). The spatial information content was similar across the groups except in trial B3 when the place fields of the aged rats were more spatially selective (spatial information content B3: young =  $0.79 \pm 0.07$ ; Ch-X =  $0.77 \pm 0.11$ ; aged =  $1.32 \pm 0.22$ ; one-way ANOVA  $t(2,22) = 5.5$ ,  $P = 0.01$ ).

Our primary interest was how the spatial representations of each group changed as the rats moved between the compartments. The rats walked between the visually identical compartments twice (A1–B2 and B3–A4), and we examined how the place cells reacted to these changes in comparison to two exposures to the same compartment (B2–B3 and A1–A4). These responses were assessed by two independent parameters, changes in firing rate (including all cells) and spatial correlations (performed only on cells that were active in both compartments).

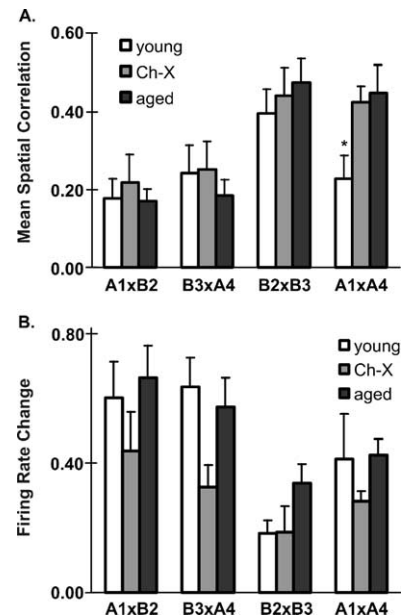


Fig. 2. Spatial correlations and firing rate changes across the trials. (A) The spatial representation correlation across each transition for each group. The pixel by pixel correlation analysis showed that spatial correlations were lower between trials across compartments than between trials within the same compartment in all groups. The groups did not differ in spatial correlation between trials involving a transition between Boxes A and B or between trials B2 and B3, but the aged and cholinergic-lesioned rats had significantly greater spatial correlations than the young rats between trials A1 and A4. The symbol “\*” denotes significance  $P < 0.05$ ; see text for specific statistics. (B) Firing rate changes at each transition for each group. For all groups there was a significantly greater change in firing rate between trials across compartments than between trials in the same compartment (see text for statistics).

The place cells of all groups showed several different reactions to the transition between the two compartments, and examples of each type of response are illustrated in Fig. 1. First, some cells were clearly controlled by the visual cues, showing the same pattern for both compartments (see Fig. 1, second cell row for each group). Second, some cells had unique representations for the two compartments and the same representation on repeated trials in the same compartment. This pattern was manifested in two ways, either by different spatial firing patterns for each environment (Fig. 1, young cell 1 A1–B2) or high activity when the rat was in one compartment and very little when it was in the other (Fig. 1, Ch-X and aged cells 1). Some cells changed their firing pattern on the first transition, but then carried the B3 firing pattern over to the period in A4 (Fig. 1, young cell 1). Lastly, a few cells changed their firing patterns on every trial. The group means

of the spatial correlation across each transition are shown in Fig. 2A.

The firing rate change was significantly higher between the different compartments than within the same compartment ( $F(1)=7.2$ ,  $P=0.01$ ), and this distinction was similar across all groups ( $F(2)=0.8$ ,  $P=0.45$ ). The magnitude of firing rate change did not differ between the groups when the rats walked between compartments (for means, see Fig. 2B; A1–B2:  $F(2,25)=0.8$ ,  $P=0.45$ ; B3–A4:  $F(2,23)=2.5$ ,  $P=0.1$ ), nor was there a group difference in firing rate changes between repetitions of the same environment (B2–B3:  $F(2,22)=2.8$ ,  $P=0.08$ ; A1–A4:  $F(2,24)=0.4$ ,  $P=0.66$ ).

The spatial representation correlations for all groups were significantly lower between compartments than within repetitions of the same compartment (compartment  $F(1)=15.6$ ,  $P=0.001$ ; compartment  $\times$  group  $F(2)=2.2$ ,  $P=0.13$ ). Spa-

Table 1  
Spatial correlations in cell ensembles of individual rats

Rat	Cells ( <i>n</i> )	A1 $\times$ B2 (%)	B3 $\times$ A4 (%)	B2 $\times$ B3 (%)	A1 $\times$ A4 (%)
<b>Young</b>					
43	1	100	100	100	100
51	2	50	100	50	100
52	2	0	0	100	50
61	4	25	25	25	0
62	1	100	100	100	0
65	1	0	0	0	0
66	2	0	100	100	No fields
77	1	0	0	No fields	100
79	2	0	0	100	100
88	2	50	No fields	100	No fields
91	3	67	33	67	33
97	2	100	50	100	100
<b>Young mean</b>	<b>1.9</b>	<b>41</b>	<b>46</b>	<b>77</b>	<b>58</b>
<b>Ch-X</b>					
45	2	100	100	100	50
53	3	0	50	100	50
54	2	0	50	100	100
55	2	100	0	50	50
63	2	50	50	No fields	100
64	2	0	0	100	100
<b>Ch-X mean</b>	<b>2.2</b>	<b>42</b>	<b>42</b>	<b>90</b>	<b>75</b>
<b>Aged</b>					
73	4	0	25	100	100
81	3	0	0	100	50
82	3	67	No fields	No fields	No fields
83	2	50	50	100	100
75	2	100	No recording in B3		50
76	2	0	0	100	100
87	4	50	100	100	75
93	6	33	50	100	60
95	2	0	0	No fields	100
98	2	0	50	50	100
<b>Aged mean</b>	<b>3.0</b>	<b>30</b>	<b>34</b>	<b>93</b>	<b>82</b>

Cells were determined to have similar spatial firing patterns across two trials if the spatial correlation reached a threshold of 0.25. Representations above this threshold were considered similar, whereas correlations below the threshold indicated two different firing patterns. The percentage of cells for each rat reflects the coherence of the ensemble within each rat. Fully coherent ensembles are reflected in 0% (all cells form new representations) and 100% (all representations remain the same), whereas a response of 50% reflects maximum discordance.

tial correlations did not differ between the groups when the rats walked from compartment A1 to B2 (see Fig. 2A for means;  $F(2,25)=0.2$ ,  $P=0.83$  or in the transition from B3 to A4:  $F(2,22)=0.3$ ,  $P=0.74$ ). As a control, when neither the visual surroundings nor the idiothetic cues changed (the bucket was not spun prior to replacing the rat into trial B3) between trials B2 and B3, all groups had high and equivalent spatial correlations (see Fig. 2A, B2–B3:  $F(2,21)=0.8$ ,  $P=0.45$ ). When several trials intervened between exposures to the same compartment (A1–A4), a Tukey post hoc test revealed that the young rats had significantly lower spatial correlations than the aged rats; and a trend in this direction was observed with the cholinergic-lesioned rats (A1–A4:  $F(2,22)=4.2$ ,  $P=0.03$ ; young versus aged:  $P=0.04$ , young versus Ch-X:  $P=0.10$ ). Table 1 shows the percentage of cells in each rat that had high spatial correlations between the trials, and Fig. 2A shows the mean spatial correlations for each group. Together the table and figure show that all groups had lowest spatial correlations between the two different arenas, highest spatial correlations between consecutive same arena trials, and the young rats had somewhat lower correlations compared to aged and cholinergic-lesioned rats between exposures to the same arena separated by several trials. Lastly, we found that the water maze learning index of aged and young rats did not predict the spatial firing responses; place cells of aged rats with poor spatial learning scores reacted in similar ways to those rats with better spatial learning (Spearman's  $\rho(15) < 0.3$ ,  $P > 0.3$ ).

#### 4. Discussion

The current experiment was motivated by previous studies that revealed an abnormal rigidity of the spatial firing patterns of hippocampal cells when aged and cholinergic-lesioned rats were placed into a visually novel environment [14,17,24,38–40]. In this experiment, rats walked between two visually identical environments, and the rigidity associated with aging and cholinergic dysfunction was not observed. As found in an earlier study where young rats walked between two identical boxes [32], place cells varied in their responses across rats and among individual cells within each rat (see Fig. 1, aged), with some cells showing the same spatial representation and others showing different representations in the visually identical environments. Furthermore, the proportion of cells changing their representations was not associated with spatial learning score, as had been observed in aged rats in previous studies [40]. These findings are consistent with the idea that the hippocampus is needed for place but not response learning [31]. The present observations advance our understanding of the hippocampal processing associated with aging in two important ways. First, the aged hippocampal neuronal network is quite capable of producing new spatial representations under some conditions. Second, the aged hippocampal network is more greatly influenced by self-motion cues than by external visual cues.

According to current theories, the hippocampus integrates information from external and internal sources [20,28]. The balance between these inputs is important for determining the spatial representation, and a change above a threshold level in either or both of them causes the generation of a new spatial representation [16]. In aged rats, the idiothetic information may have increased influence over the representations, as suggested by four lines of evidence. First, spatial representations are often maintained between visually distinct environments [38–40] but differ between identical environments entered by self-movement (current experiment). Second, when forced to rely on external visual cues, aged rats sometimes create different spatial representations even for the same environment [2,39], whereas when self-motion cues are sufficient, aged rats form stable representations (current experiment). Third, the spatial representations of aged rats are delayed in switching from dependence upon internal to external cues when external landmarks predicted the goal location while internal cues did not [30]. Fourth, aged rats [1] and monkeys [26] rely more on a response strategy than on a place strategy, consistent with an abnormal emphasis on idiothetic information. Such a strategy shift would lead to the impaired spatial learning, as characterizes aged animals (for review, see [7,25]).

Increased dependence on idiothetic information does not fully account for the current results. If idiothetic information had completely dominated over visual information in aged rats, we would expect a *higher* proportion of altered spatial representations across the A1–B2 and B3–A4 transitions in aged rats than in young rats. This was not observed. Furthermore, more of the cells in aged rats maintained the same representations in A1 and A4 than young rats (although cells of all groups showed the same representations between trials B2 and B3), similar to an earlier report of increased stability in the same aged rats across two exposures to a familiar environment intervened by exposure to an altered environment [40]. It appears therefore that spatial representations of aged and cholinergic-lesioned rats are rigidly locked to visual cues, in that, once created, they are less prone to further modifications by experience. Aged rats [37] as well as aged humans [15] have been shown to acquire less information than young subjects about environmental landmarks. Thus, when limited to only a subset of the information, the spatial representations of aged memory-impaired rats may appear more stable than those of young rats when subjected to subtle changes in the environment.

Three age-associated neurobiological changes may underlie this impaired processing. First, the hippocampus of aged rats is less receptive to experience-dependent changes in synaptic plasticity (for review see [29]). Second, the number of synaptic contacts from entorhinal cortex to dentate gyrus and CA3 is decreased with aging, whereas the CA3 auto-associative network remains intact [10,27,34]. Third, the medial septum provides less cholinergic modulation to the hippocampus of aged animals [5,11,23,35]. These changes may well set the stage for decreased cortical input detailing

external changes and increased pattern completion by the hippocampal network [12]. The present finding that place cells of rats with cholinergic lesions respond similarly to those of aged rats supports this view.

The current study demonstrates that aged memory-impaired rats and cholinergic-lesioned rats do form separate spatial representations for two visually identical environments when the rats are allowed to walk between them, in contrast to the rigidity of spatial representations when these animals are exposed passively to visually different environments. The current results show that the rigidity of hippocampal spatial representations in aged rats stems from the combination of two processes. First, aged rats have increased reliance on self-motion cues accompanied by diminished use of external visual cues. Second, changes in the dynamics of their hippocampal networks work against plasticity and favor pattern completion of pre-existing representation over the creation of new spatial representations. Ultimately, these changes in information processing may underlie the impairment in spatial memory performance by aged rats.

## Acknowledgements

This work was supported by the National Institute on Aging, grant AG09973, and by the Academy of Finland, grant 46000. We thank Dr. Matthew Shapiro for much of the analysis software and Irina Gureviciene for electrode construction.

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