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Impaired Creation of Cognitive Maps from Active Exploration During Normal Aging

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ABSTRACT

Age-related decline in spatial navigation may be caused by difficulties in the creation of cognitive maps. However, selectively assessing cognitive mapping abilities in navigation tasks may be difficult, as multiple cognitive processes are involved in spatial navigation. Using a simple exploration and recall versus recognition task in virtual mazes, this study investigated the mapping abilities in healthy elderly individuals. Elderly and young control subjects were asked to create cognitive maps of virtual mazes by exploring them during an unlimited time. Exploration was followed by an immediate free recall task (i.e. drawing the map of the virtual environment) and a recognition task involving identification of the correct map among several choices. Elderly subjects required more time than young adults to explore the virtual mazes. Despite longer exploration times, free recall, including bifurcation and metric errors, and recognition performance were lower in elderly than in young adults. Because recognition performance reflects encoding processes, these results suggest that cognitive mapping abilities are impaired during aging. This, in turn, may explain age-related difficulties in spatial navigation.

Keywords: Spatial Memory; Spatial Navigation; Cognitive Map; Aging

Introduction

Spatial navigation refers to the ability to orientate in a novel or well-known environment and to plan a path to reach a location within this environment [1, 2]. Navigation in an environment relies on the creation of a mental representation of the spatial layout of the environment, called a cognitive map [3]. Acquisition of cognitive maps is derived from active exploration of novel environments and involves multiple cognitive processes and functions [4]. These cognitive maps are stored in long-term spatial memory and are retrieved when the individual again visits the environment. Retrieval of cognitive maps can be assessed from any perspective or vantage point [5]. Cognitive maps do not represent a specific experience, but an overarching relational memory built by integrating a number of memories pertaining to a spatial experience [6].

Numerous studies have consistently shown that spatial navigation is impaired in elderly individuals [7, 8, 9]. Studies assessing navigational abilities generally consist of a learning phase, in which subjects are required to actively explore a virtual environment in order to create a cognitive map of this environment; followed by a test phase, in which subjects have to reach several locations within this environment from a starting point. Performance is assessed by the distance traveled, the time to reach the desired location and/or the number of errors. In these tasks, elderly individuals generally travel a longer distance, need more time and show more errors than younger adults. Impaired navigational performance in elderly individuals is thought to be due to deficiencies in the creation and use of cognitive maps (i.e. retrieval of cognitive maps in spatial memory [10, 11]. However, it is difficult to distinguish impaired creation from impaired retrieval of cognitive maps, since memory performance is measured using navigation tasks, and successful navigation necessitates both the creation of an accurate cognitive map of the environment and the ability to use this cognitive map for orientation within the environment.

This study hypothesized that deficiencies in the creation of cognitive maps explain age-related navigational difficulties. To specifically assess the ability of elderly individuals to create cognitive maps, elderly and younger subjects were instructed to freely explore virtual mazes and to learn the configuration of these mazes. The creation of cognitive maps was assessed by free recall (i.e. drawing a map of the previously explored maze), and by recognizing the correct map among several choices. Assessing spatial memory performance using free recall and recognition may distinguish between deficiencies in the creation of cognitive maps and deficiencies in retrieving cognitive maps from memory. Thus, age-related deficiencies in the creation of cognitive maps were hypothesized to result in impaired performance on both free recall and recognition, whereas deficiencies in the retrieval of cognitive maps from memory were hypothesized to result in impaired performance on free recall, but improved performance on recognition.

Materials and Methods

Participants

This study recruited 29 elderly subjects (12 men, 17 women, of mean ± SD age 66.7 ± 4.8 years; range: 60-75 years) and 24 young adults (13 men, 11 women, of mean ± SD age 24.0 ± 2.9 years) aged 20–30 years. All participants were right-handed and had normal or corrected-to-normal vision. None had any neurological or psychiatric history, or was taking any drug that could affect their cognitive functioning. Elderly subjects were also screened for dementia by detailed neuropsychological examination, including tests of global efficiency, episodic memory, visuospatial abilities, language, executive functions and mental disorders such as anxiety and depression. All elderly subjects included in this study had a Mini Mental State Examination (MMSE; [12] score > 27, confirming absence of dementia. None had a score >5 suggesting depressive disorder on the Geriatric Depression Scale (GDS; [13] or a score >55 suggesting anxiety disorders on the State-Trait Anxiety Inventory (STAI; [14] Scores at the neuropsychological examination are summarized in Table 1.

Since the tasks were computerized, and computer skills were likely to affect their performance, each participant was administered a French version of a questionnaire assessing their computer skills [15].

All subjects gave written informed consent prior to inclusion in the study. The study was approved by the Ethic Committee Est II and conducted in accordance with the Declaration of Helsinki.

Tests	Elderly subjects		Young subjects		
	Mean	SD	Mean	SD	
Depression and anxiety					
GDS	1.31	1.62	Not performed		-
STAI-A	29.28	7.64	27.50	6.04	t[51] = 0.91 ; p = 0.37
STAI-B	32.10	7.70	30.71	5.30	t[51] = 0.74 ; p = 0.46
General cognitive efficiency					
MMSE	28.97	1.03	Not performed		-
Raven's progressive matrices (/12)	9.07	2.02	9.63	1,52	t[51] = -1.09 ; p = 0.28
Visuo-spatial functions					
VOSP position discrimination (/20)	19.83	0.46	19.79	0.50	t[51] = 0.27 ; p = 0.79
VOSP digit localization (/10)	9.07	1.20	9.83	0.47	t[51] = -1.15 ; p = 0.26
VOSP cube analysis (/10)	9.86	0.43	9.92	0.28	t[51] = 1.04 ; p = 0.30
Visual Memory					
Rey's Complex Figure – copy (/36)	35.03	1.30	35.42	1.00	t[51] = -1.16 ; p = 0.25
Rey's Complex Figure – immediaterecall (/36)	19.41	5.16	21.92	5.54	t[51] = -1.67 ; p = 0.10
Rey's Complex Figure – delayed recall (/36)	19.69	5.20	21.71	4.83	t[51] = -1.43 ; p = 0.16
Verbal Memory					
RAVLT 1st recall (/15)	6.59	2.24	7.58	1.55	t[51] = -1.81 ; p = 0.08
RAVLT total recall (/75)	54.07	8.80	56.08	4.23	t[51] = -1.01 ; p = 0.32
Short term and working memory					
Digit span	6.00	1.11	6.50	0.96	t[51] = -1.70 ; p = 0.10
Digit span backward	4.76	1.19	5.04	0.98	t[51] = -0.91 ; p = 0.37
Executive functions					
FAB (/18)	**17.21**	**1.09**	**17.83**	**0.47**	**t[51] = -2.56 ; p = 0.01**
Verbal fluency - letter P (N correct)	27.38	7.68	30.04	4,94	t[51] = -1.44 ; p = 0.16
Verbal fluency - animals (N correct)	37.24	9.35	39.96	5.24	t[51] = -1.24 ; p = 0.22
TMT-A (sec)	**36.90**	**10.67**	**30.75**	**6.15**	**t[51] = 2.45 ; p = 0.02**
TMT-B (sec)	92.83	32.70	80.63	12.10	t[51] = 1.70 ; p = 0.10

Tests	Elderly subjects		Young subjects		
	Mean	SD	Mean	SD	
Language					
DO 80 (/80)	79.66	0.71	79.92	0.28	t[51] = -1.67 ; p = 0.10

Table 1: Mean scores and standard deviation obtained by the elderly subjects at the neuropsychological examination. Abbreviations: GDS: Geriatric Depression Scale; STAI-A: Stait-Trait Anxiety Inventory part A (state); part B (trait); MMSE: Mini Mental State Examination; VOSP: Visual Object and Space Perception; RAVLT: Rey's Auditory Verbal Learning Test; FAB: Frontal Assessment Battery; DO 80: French Denomination test; TMT: Trail Making Test.

Stimuli

The virtual environment consisted of 16 mazes created using Google Sketchup pro 8 software (2007 navigation Trimble limited). The walls of each maze were 2 m high and made of grey bricks. A 3 m high palm tree was located on the outside of the maze, but was visible from the inside, to constitute a landmark helping participants to orientate themselves in the mazes. Difficulty level varied from 1 to 4 as a function of the number of hallways in the mazes: difficulty level 1: 3 hallways; difficulty level 2: 4 hallways; difficulty level 3: 5 hallways and difficulty level 4: 6 hallways. There were 4 mazes per difficulty level.

Procedure

Participants were seated in a dimly lit room in front of a computer screen (21 inches, 75 Hz) displaying virtual the stimuli. In each trial, the participants were allowed to freely explore one of the 16 mazes to create a mental representation of that maze. Immediately afterwards, the participants were asked to draw a map of the explored maze (i.e. free recall) and then to identify the correct map of the maze among four choices (i.e. recognition). The next trial began with the free exploration of another maze, followed by free recall and recognition. Mean total time to complete the task was 60 min, with the time varying across participants because exploration time was not limited. Before the task, each subject participated in a training phase involving six simple mazes, allowing subjects to familiarize themselves with the virtual environments and with navigation within the mazes. Performance was not recorded during the training phase and therefore not included in the analyses.

Exploration phase

Each trial started at the entrance of one of the 16 mazes, with the start point represented by a blue circle on the ground. Participants were instructed to explore the maze to learn its spatial configuration. They were also informed that exploration time was not limited and that they could visit the hallways as many times as they wanted. We facilitated navigation within the virtual mazes for elderly subjects, who are less familiar with virtual environments than young adults. To navigate within the mazes, participants selected the chosen direction, indicated by white arrows on the ground (See Figure 1A), by pressing arrow keys on a computer keyboard; i.e. the left and right arrows to turn left and right, respectively, and the up arrow to go forward. Once the participants had chosen a direction, they automatically moved forward at a constant speed of 1.5 m/s to the next intersection, where they had to again choose a direction. The speed of rotation at intersections was 25 degrees/s. A blue line appeared on the ground when participants went down a hallway, which helped keeping track of paths already traveled (See Figure 1A). When participants believed they had memorized the spatial configuration of the maze, they ended the trial by pressing the "escape" key on the keyboard trial. Exploration times were recorded.

Free recall task

Immediately after exploration of a maze, participants were asked to draw a map of that maze on a grid sheet. The entrance, signified by a blue dot, the entrance hallway and the palm tree were represented on the grid sheet. The time allowed to draw the map was not limited. The accuracy of each drawing was evaluated using a template reporting the correct map, with the correct length of each hallway and the correct number of turns (See Figure 1B). Two types of errors were recorded, metric and directional errors. Metric errors consisted of an incorrect number of squares (i.e. units of length) in each hallway, with each missing or excess square rated as +1 point, and a score of 0 representing no errors. Bifurcation errors consisted of wrong turns, with each correctly reported turn scored as +1 point and each missing or incorrectly reported turn scored as -1 point, such that a higher score represented fewer errors.

Recognition task

After the free recall task, four maps were presented on the computer screen, one being the correct map and the other three being incorrect maps of the previously explored maze (See Figure 1C). Incorrect maps differed from the correct map by, for example, the position of the palm tree relative to the entrance, or by being a mirror image of the correct map. Each correct answer was scored as one point, with a maximum score on this task of 16.

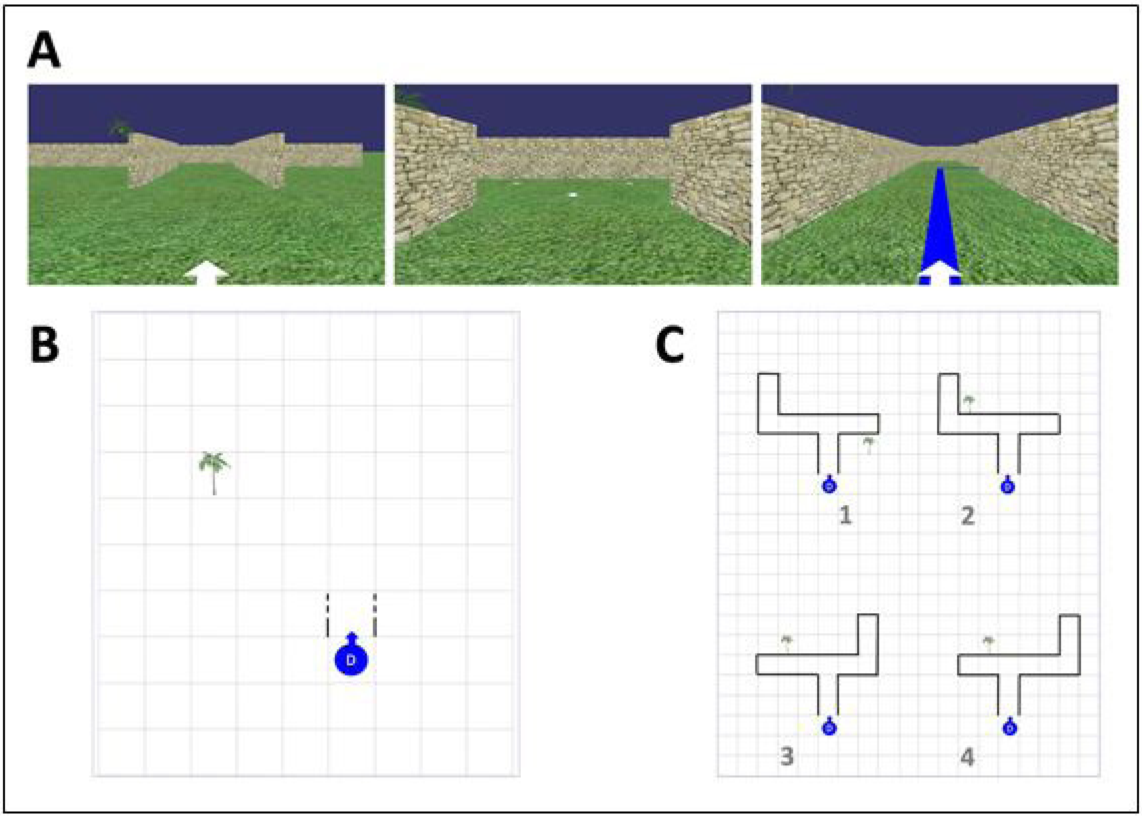

Figure 1: A. Example of a virtual maze, showing views of the mazes during active exploration. White arrows on the ground show possible directions. A blue line on the floor represents a path already travelled.

B. Example of a grid sheet provided for free recall of the maps created through active exploration. The starting point (i.e. the blue dot), the entrance hallway and the palm tree are shown.

C. Example of one recognition trial. One of the 4 maps represents the correct map of the explored maze, whereas the three other maps differed from the correct map in the location of the palm tree relative to the entrance, or were mirror images of the correct map.

Statistical analyses

Scores on the questionnaires assessing computer skills, times to explore the mazes and recognition performance were compared in the young and elderly groups using Student's t-tests.

Metric and bifurcation errors on the free recall task were compared in young and elderly subjects using repeated measures ANOVA, with age group (young vs elderly) as a between subject factor and difficulty levels (1–4) as a within-subject factor. Newman-Keuls post-hoc paired comparisons were performed when ANOVA showed significant effects, defined as p < 0.05.

To examine the link between memory performances and cognitive mapping abilities, we conducted Pearson correlations between verbal and visual memory scores obtained by the elderly participants during the neuropsychological examination (see section 2.1 and Table 1) and their performance in free recall and recognition in the spatial memory task. These analyses were conducted only on elderly subjects, since only elderly subjects performed the neuropsychological tests.

The relationship between exploration times and metric and directional errors was analyzed for all subjects using Pearson correlations. Bonferroni correction was applied in case of multiple analyses.

Results

Computer skills

A comparison of computer skills in the young and elderly subjects showed that younger subjects had greater computer expertise (t□51□ = 4.53; p < 0.01). Because computer skills may explain, at least in part, subjects' performance on the spatial memory task, we took this factor into account in covariance analyses (ANCOVA).

Exploration time

Mean time taken by subjects to explore the mazes was significantly greater for elderly (mean = 139.30 s; SD = 63.18 s) than for younger (mean = 82.20 s; SD = 29.82 s) subjects (t[51] = 3.50; p < 0.01).

Free recall task

Metric errors

The mean numbers of metric errors for young and elderly participants at each level of difficulty are shown on Figure 2. ANOVA showed that the number of errors was significantly greater in elderly than in young subjects (F[1;51] = 43.79; p < 0.01; η2 = 0.46). This significance was confirmed by covariance analysis that took computer skills into account (F[4;51] = 5.54; p < 0.01).

There was an interaction effect between age and difficulty level (F[3;153] = 7.02; p< 0.01; η2 = 0.12). Newman-Keuls post-hoc tests revealed that the numbers of metric errors were higher in older than younger subjects for each difficulty level (p < 0.01 in each case). The numbers of metric errors increased with difficulty level in older subjects (p < 0.01 in each case). In younger subjects, the number of metric errors differed between difficulty levels (p < 0.01 in each case), except between level 1 and 2 (p = 0.14) and between level 3 and 4 (p = 0.87).

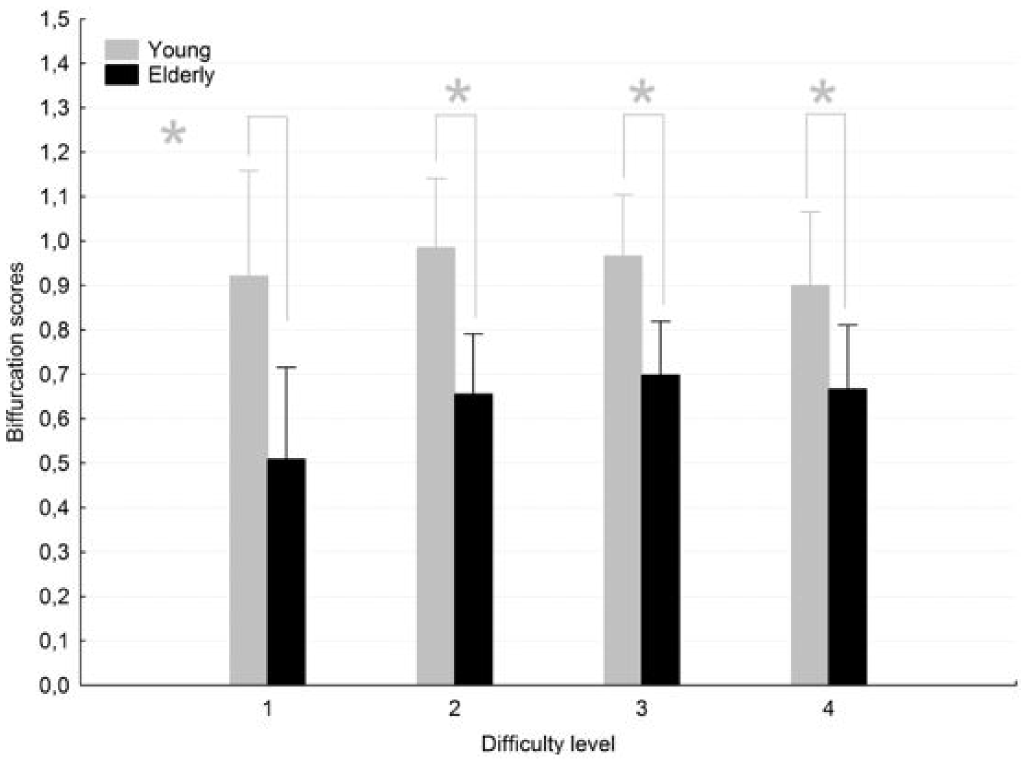

Figure 2: Mean number of metric errors made by young (grey bars) and elderly groups (blackbars) at each level of difficulty. Significant differences are marked with an asterisk ($p < 0.05$). Error bars indicate the standard deviation

Bifurcation scores

The mean bifurcation scores for the two groups at each level of difficulty are shown on Figure 3. ANOVA showed that bifurcation scores were lower in elderly than in young subjects ($F[1;51] = 12.95$; $p < 0.01$; $\eta 2 = 0.21$), reflecting more errors in the elderly group. This finding was confirmed by ANCOVA, after taking computer skills into account ($F[4;51] = 3.32$ $p = 0.02$).

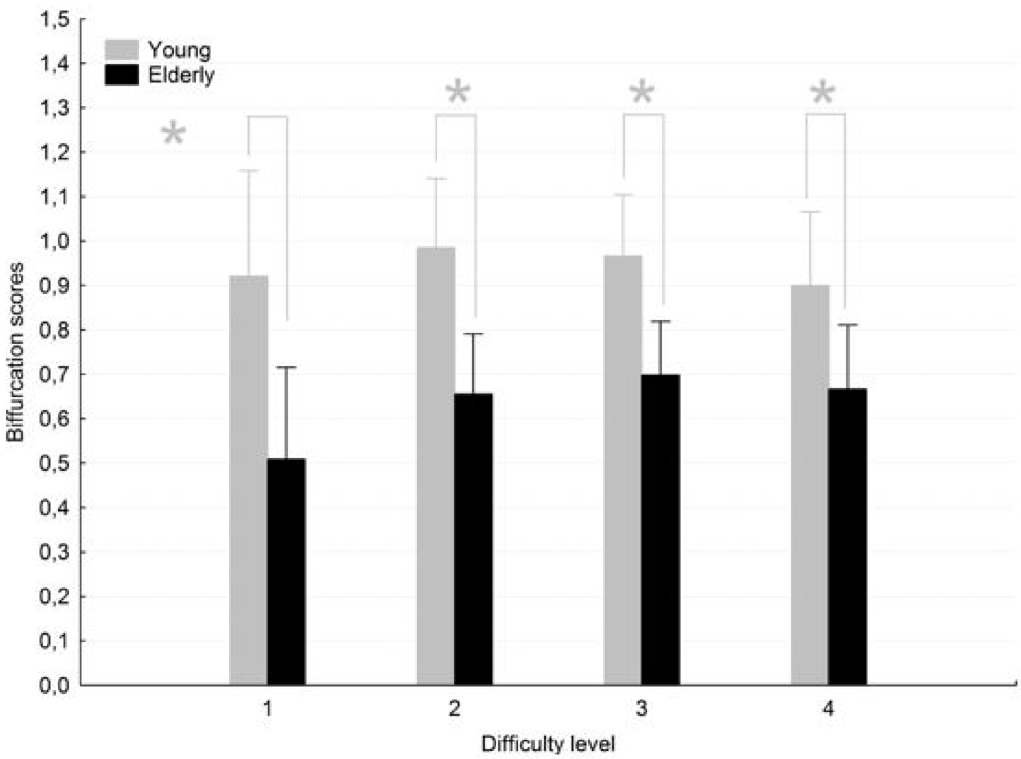

Figure 3: Mean bifurcation scores in young (grey bars) and elderly (black bars) subjects at each level of difficulty. Higher bifurcation scores represented fewer errors. Significant differences are marked with an asterisk ($p < 0.05$). Error bars indicate the standard deviation

There was no interaction effect between age and difficulty level on bifurcation scores ($F[3;153] = 0.31$; $p = 0.82$).

Recognition task

Student's t-test revealed that recognition scores were significantly lower in the elderly than in the young group (t□51□ = 4.20; $p < 0.01$).

Correlational analyses

Correlations between the spatial memory task an neuropsychological tests

Pearson correlations were conducted between memory scores at the neuropsychological examination (i.e. Rey's complex figure copy; immediate recall; delayed recall; Rey's auditory verbal learning test total score) and i) metric errors during free recall of the spatial memory task ii) bifurcation scores during free recall of the spatial memory task and iii) recognition of the spatial memory task. Bonferroni correction for multiple analyses was applied, resulting in a statistical threshold of $p < 0.004$ (i.e. 0.05 / 12 correlations). No correlation reached statistical significance. We found a trend for significant correlation between metric errors and Rey's complex figure delayed recall ($r = 0.44$; $p = 0.03$).

Correlations between exploration times and performance at the spatial memory task
Pearson correlations were conducted between exploration time and performance parameters (i.e. metric and directional errors during free recall and recognition scores) at the spatial memory task. Bonferroni correction for multiple analyses was applied, resulting in a statistical threshold of $p < 0.017$ (i.e. 0.05 / 3).

We found that exploration time was positively correlated with the number of metric errors ($r = 0.31$; $p = 0.02$) and negatively correlated with directional errors ($r = 0.32$; $p = 0.02$), although these two correlations did not reach the significance threshold. In other words, the longer subjects explored the virtual mazes, the more metric errors they made, but the less directional errors they made. We also found that exploration time was positively correlated with recognition scores ($r = 0.3$; $p = 0.004$), such that the longer subjects explored the virtual mazes, the better they performed in the recognition task.

Discussion

This study was designed to assess spatial memory in elderly individuals, focusing on the process of creating cognitive maps of virtual mazes. We hypothesized that spatial memory difficulties in aging may be explained by deficiencies in the creation of cognitive maps of novel environments. In this study, subjects had to create cognitive maps of virtual mazes through active exploration. Cognitive mapping abilities were evaluated by subsequent free recall and recognition of the maps of the mazes. We hypothesized that impairment of both free recall and recognition performance would reflect impaired creation of cognitive maps. We found that performance on both free recall and recognition of cognitive maps was impaired in elderly participants, suggesting that creation of cognitive maps becomes impaired during normal aging. This was confirmed by the elderly participants requiring longer exploration times yet still not achieving the same level of performance as young adults. These results are not likely due to the lower computer skills of elderly subjects, as shown by the results of covariance analyses controlling for this factor.

These results are in agreement with those of previous studies, which showed that spatial memory performances were lower in elderly than in young adults [6, 10, 16]. However, the previous studies did not investigate whether aging specifically impairs the ability to create cognitive maps of novel environments. In fact, these studies showed that elderly participants required more time and made more errors than young adults when navigating in an environment, results that can be explained by both impaired creation of cognitive maps and by impaired retrieval and use of cognitive maps to orientate. In contrast to these previous studies, the present study did not assess the ability of subjects to use a cognitive map to navigate in an environment. Rather, it evaluated the ability of subjects to formulate a cognitive map of a novel environment using free recall and recognition of cognitive maps.

Cognitive mapping abilities in elderly participants are unlikely explained by memory abilities. Indeed, elderly individuals obtained scores in the normal range tests of verbal and visual memory during a neuropsychological examination prior to the virtual spatial navigation task. This suggests that performances of elderly subjects at the spatial memory task are specifically explained by difficulties in the creation of cognitive maps.

Free recall and recognition are both ways to test retrieval processes, but they rely on different neural underpinnings. Whereas free recall involves the prefrontal cortex, recognition mainly involves the hippocampus [17].

Moreover, unlike free recall, recognition is a re-experience of a stimulus and relies on a match between the representation of that stimulus stored in memory and an environmental context (Norman & O'Reilly, 2003). Thus, free recall performance may be impaired by alterations of search strategies in memory. If, however, the stimulus has been properly encoded, the provision of external support improves performance, as during recognition. Evaluating recognition performance therefore allows the specific targeting of hippocampal functions.

The impaired creation of cognitive maps in elderly subjects shown in the present study suggests age-related alterations in the hippocampus, a brain area crucial for spatial memory [18]. Hippocampal volume loss [19] and modified hippocampal activity [20] have been reported during normal aging, which may explain the impaired creation of cognitive maps in elderly individuals. This finding is in accordance with the results of functional magnetic resonance imaging, which showed that hippocampal activity during a spatial navigation task was lower in elderly than in young adults [16]. Moreover, the spatial memory performance of elderly individuals was found to correlate with hippocampal volume [21-22].

Founding source

None.

Authors statement

Framework design: T. Pebayle, O. Després & S. Lithfous. Acquisition of data: M. Courtès & O. Couval. Analysis and interpretation of data: O. Després & M. Courtès. Drafting of the manuscript: S. Lithfous & O. Després. Critical revision of the manuscript for important intellectual content: S. Lithfous & O. Després. Supervision: S. Lithfous & O. Després. All authors interpreted the data, revised the manuscript, and approved the final draft.

Disclosure statement

No potential conflict of interest was reported by the authors.

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