HAL
open science

# How the Learning Path and the Very Structure of a Multifloored Environment Influence Human Spatial Memory

Laurent Dollé, Jacques Droulez, Daniel Bennequin, Alain Berthoz, Guillaume Thibault

## To cite this version:

Laurent Dollé, Jacques Droulez, Daniel Bennequin, Alain Berthoz, Guillaume Thibault. How the Learning Path and the Very Structure of a Multifloored Environment Influence Human Spatial Memory. Advances in Cognitive Psychology, 2015, 11 (4), pp.156 - 162. 10.5709/acp-0180-5 . hal-01380024

**HAL Id: hal-01380024**

**https://hal.science/hal-01380024v1**

Submitted on 14 Oct 2016

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## Abstract

Few studies have explored how humans memorize landmarks in complex multifloored buildings. They have observed that participants memorize an environment either by floors or by vertical columns, influenced by the learning path. However, the influence of the building's actual structure is not yet known. In order to investigate this influence, we conducted an experiment using an object-in-place protocol in a cylindrical building to contrast with previous experiments which used rectilinear environments.

Two groups of 15 participants were taken on a tour with a first person perspective through a virtual cylindrical three-floored building. They followed either a route discovering floors one at a time, or a route discovering columns (by simulated lifts across floors). They then underwent a series of trials, in which they viewed a camera movement reproducing either a segment of the learning path (familiar trials), or performing a shortcut relative to the learning trajectory (novel trials).

We observed that regardless of the learning path, participants better memorized the building by floors, and only participants who had discovered the building by columns also memorized it by columns. This expands on previous results obtained in a rectilinear building, where the learning path favoured the memory of its horizontal and vertical layout. Taken together, these results suggest that both learning mode and an environment's structure influence the spatial memory of complex multifloored buildings.


*Keywords :* navigation and spatial memory, spatial cognition, representation.

# How the learning path and the very structure of a multifloored environment influence human spatial memory

Laurent Dollé, Jacques Droulez, Daniel Bennequin, Alain Berthoz and Guillaume Thibault

## Introduction

While the brain's mechanisms for spatial navigation have been extensively studied for planar environments, little is known about human spatial memory in 3D environments like multifloored buildings (Montello & Pick, 1993; Christou & Bülthoff, 1999; Wilson, Foreman, Stanton, & Duffy, 2004; Hölscher, Meilinger, Vrachliotis, Brösamle, & Knauff, 2006; Büchner, Hölscher, & Strube, 2007; see also Jeffery, Jovalekic, Verriotis, & Hayman, 2013 for a survey). While Montello and Pick (1993) and Hölscher et al. (2006) suggest that humans recall the positions of landmarks in a building better within than across floors (representation by floors), in Büchner et al. (2007), participants regionalized the building either by floors or by staircases. However the tendency to memorize buildings by floors might stem from the learning mode since in these studies participants mainly explored buildings by floors. This is why Thibault et al. (2013) studied the acquired memory of landmark locations in a virtual three-floored rectilinear building, in which each floor was a straight corridor divided into three rooms, each one containing a particular object. At learning, participants passively visited the virtual building by following a dedicated learning path: either by floors (named floor learners) or by columns (named column learners) and were instructed to memorize the location of each object. At test, the camera moved from a room containing an object to an adjacent empty room and participants had to remember and

select the object that was located in this room out of four objects. The tests used either a learning path that was familiar to the learner (i.e. by floor for floor learners) or novel (i.e. by column for floor learners). Floor learners obtained better results and shorter reaction times (RTs) in familiar tests than in novel tests, and crucially, so did column learners, which clearly demonstrates the influence of learning path on the acquired memory of landmarks in a building.

However, due to its relative simplicity, the environment's geometry, with its rectilinear corridors, might have been perceived by some participants as a frontal plane (and not as a building with several 2D floors). This simple structure may have reduced the potential influence of the environment's structure on the acquired memory. The present study investigated the influence of learning path in a cylindrical building this time, using the same protocol as Thibault et al. (2013), to contrast the influence of a cylindrical versus a rectilinear structure. We expected the same learning path to have a selective influence depending on the structure.

# 1. Method

## 1.1. Participants

Thirty participants (20 males and 10 females) took part in this study. They are employees of Electricité de France (the main electricity provider in France). None was active in the field of 3D navigation. Their ages ranged from 22 to 54 years (with an average age of 39). All participants had normal or corrected-to-normal vision. This study was approved by the local Ethics Committee. Participants gave their informed consent before starting the experiment.

### 1.2. Apparatus

We used a cylindrical virtual building (Figure 1) modelled with SolidWorks and rendered in real-time using Virtools. The environment was displayed on a 30x48 cm monitor at a refresh frequency of 60 Hz with a screen resolution of 1600x1200 pixels and a contrast of 2500:1. The viewers sat about 50 cm from the monitor resulting in a horizontal field of view of 51°. The virtual field of view was set at 73°. The building consisted of three superposed circular corridors (with a 9 m radius), which were themselves divided into three rooms whose size was equivalent to one third (120°) of the corridor. Two cylindrical walls delimited the corridors: an internal wall (7 m radius), placed in the centre of the building, prevented participants from seeing objects in other rooms, while an external wall prevented participants from seeing outside. As each room included an entrance and an exit, plus ladders to move above and below, it was connected to the next room horizontally and vertically. Stimuli consisted of nine virtual objects: a fireplace, a bar, a children's writing desk, a bookcase, a boiler, a kitchen unit, a blackboard, a drawer and a piano. Each of the nine objects were stood against the external wall and placed in the middle of a different room in the virtual building.

### 1.3. Procedure

This object-in-place experiment consisted of a learning stage followed by a testing stage, with the whole experiment taking about 45 minutes to complete. Since we tried to minimize the difference with the methods of Thibault et al. (2013), unless stated otherwise, our procedure and parameters are equal or equivalent to those chosen in Thibault et al. (2013).

*Learning stage*

Participants viewed the virtual building's corridors. This passive visit led them through the full set of floors and objects twice (number determined in a pilot study). The duration of each exploration was 60 s at a constant speed of 1.35 m/s.

Two learning conditions were tested, each involving 15 different subjects.

a) In the **floor-learning** condition, participants sequentially discovered all the objects on a floor before moving to the floor above (Fig. 1a). Contrary to Thibault et al. (2013) the direction of the trajectory was the same throughout all the floors (there was no reversing of the travelling direction between floors).

b) In the **column-learning** condition, they discovered all the objects in a column before moving to the next column (Fig. 1b).

Therefore, in the floor-learning condition, the trajectory consisted of six floor segments and two column segments, whereas in the column-learning condition, it consisted of two floor segments and six column segments.

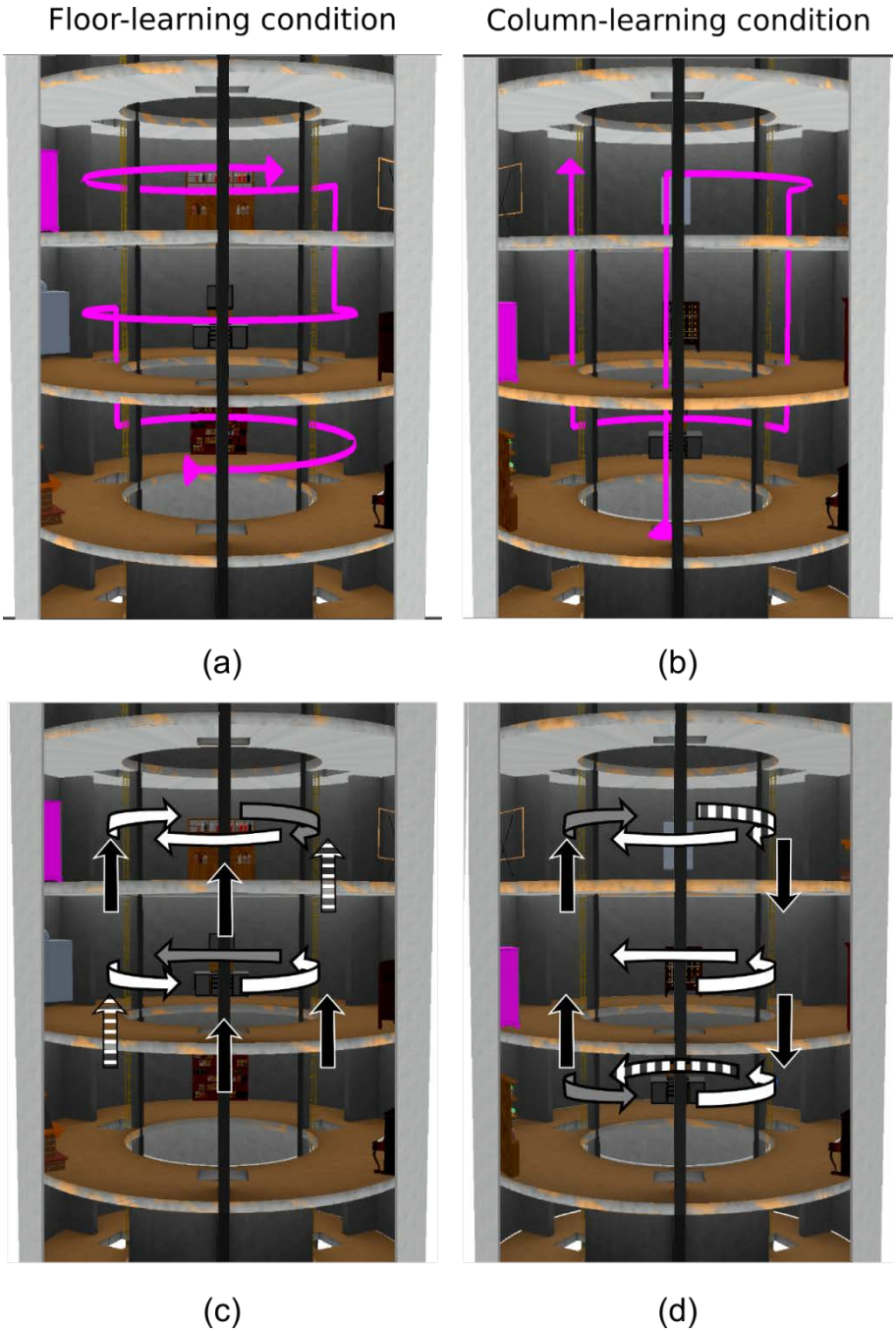



Figure 1. Cutaway of the virtual building. Trajectories (pink ribbons) followed during the learning phase for the Floor-learning group and (b) the Column-learning group. Trial segments for (c) the Floor-learning group and (d) the Column-learning group. Segments are depicted by white arrows for floor trials, black arrows for column trials, grey arrows for closure trials and white striped arrows for mis-categorized trials (not analyzed).

Objects were seen in the same order in each learning trajectory, since they were placed in the building accordingly for each group. We have controlled neither the grouping nor the order of objects, since there exists a multiplicity of possible relations (per color, shape, use, name, etc.). But we counterbalanced these individual choices by recruiting a large number of subjects. The environment was arranged so that objects were always viewed one by one for about 3 s. Participants were informed that each room contained only one object, but they were not told the total number of objects or floors, or that the building was cylindrical. They never saw the building from the outside, nor could they see outside the building. In consequence it was not possible for them to anchor their orientation on distal cues (see, e.g., Knierim and Hamilton, 2011 for a review). They were also instructed to pay attention to the spatial relations between the objects so they could build a "mental representation" of the building.

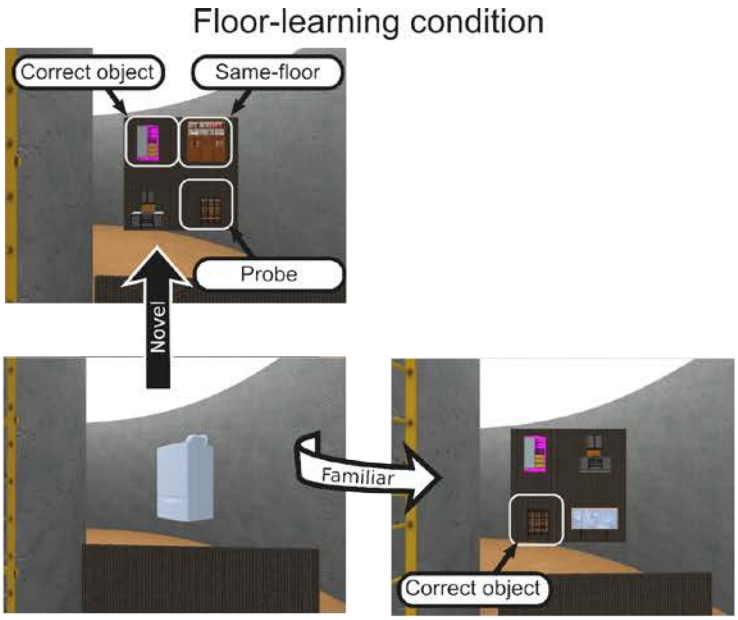
While the camera moved in facing direction within a same floor, vertical transitions were performed sideways, so that the participant could see the ladder scrolls on the left of his field of view. A small wall was added in front of the objects so that objects from both floors could not be seen simultaneously during the vertical transition. At the end of the first tour, a text appeared informing the participants they had been relocated to the starting point.

*Testing stage*

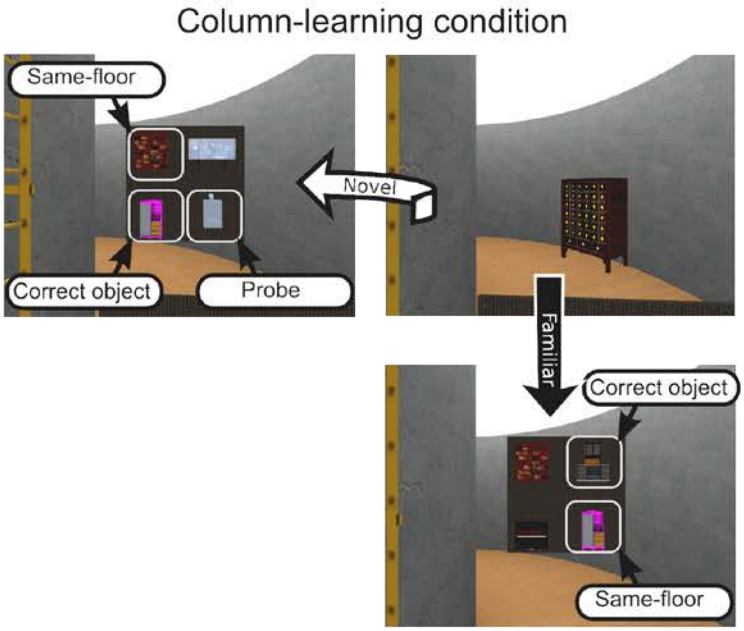
Participants underwent trials consisting of a camera movement, called a segment, from one room to an adjacent room (Fig. 1c and d). In each trial, a fixation cross appeared for about 1 s before the camera was located to a room where the participant could see the corresponding object (Fig. 2a and b, starting screen).

The camera then moved for about 15 s to an adjacent empty room either on the same floor (floor trial) or in the same column (column trial). Thus, depending on the learning

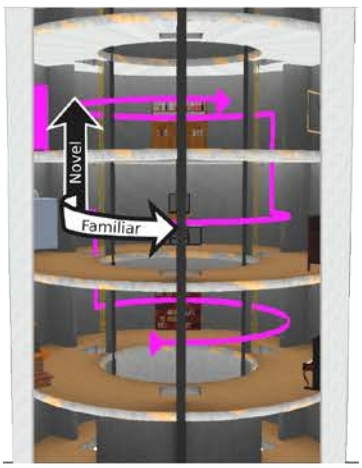
condition, a trial could either replicate a segment of the learning path (familiar segment) or perform a shortcut relative to the learning trajectory (novel segment), as shown in Figures 2c and d. Hence, familiarity of the trial is defined here as the consistency between the direction of movement on the test segment and the direction of the movement in the same segment during learning. During learning, the cylindrical nature of the building was never explicitly stated: for instance, as shown on Figure 1a in third floor, participants had visited the bar/secretary and secretary/blackboard segments, but not the blackboard/bar segment. We called this last segment a “closure” segment, as it would have revealed that the floor is in fact a closed circular path. In order to assess if participants had inferred the cylindrical nature of the building, we also tested two closure segments. Two other segments had been experienced during the learning stage but were at odds with the main direction of the learning condition: they were discarded from the results analysis and called mis-categorized segments, since they could not be categorized into any family of segments. Therefore, for each learning condition, out of the 10 trials analyzed, six were horizontal (four floor and two closure segments) and four were vertical (four column segments). In total, two series of 12 segments (the 10 segments analyzed plus the mis-categorized ones), ordered in a pseudo-random manner, were run (Fig. 1c and d). All possible segments were not run, to keep reasonable the whole duration of the experiment.


Floor-learning condition
Correct object
Same-floor
Probe
Novel
Familiar
Correct object

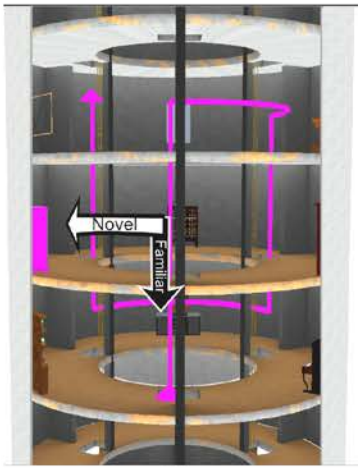
(a)


Column-learning condition
Same-floor
Novel
Correct object
Probe
Familiar
Correct object
Same-floor

(b)


Novel
Familiar

(c)


Novel
Familiar

(d)

Figure 2. Examples of floor and column segments starting from the same room. (a) Start screen (bottom-left), arrival screen (top-left and bottom-right) corresponding to the floor-learning condition. (b) Start screen (top-right), arrival screen (top-left and bottom-right) corresponding to the column-learning condition. (c) Arrows showing trial segments on the floor trajectory. (d) The same for the column trajectory.

After 500 ms, four objects appeared (see Fig. 2a and b, arrival screens) and participants were required to choose the one that was originally located in that room (arrival object, appearing simultaneously with three distractor objects) by pressing the corresponding key among four keyboard predefined keys. Participants were encouraged to answer as accurately and as quickly as possible. Performances and RTs were recorded. Each trial for the floor learning condition was paired with a trial for the column learning condition by sharing the same departure object. It was not possible to keep the same arrival objects for novel segments for both conditions, since two objects standing next to each other in the floor-learning condition were not superposed in the column-learning condition.

The trials in which the segment was novel included a particular distractor, the probe distractor, an object adjacent to the departure object along the learning path. Thus, in floor learning condition, this object is situated in a room on the same floor as the departure object, and in a novel trial (for this condition) it appeared with three other objects in the room of the floor above (similarly, in column learning condition it is situated in a room on the same column as the departure object, and in a novel trial it appeared in a room of the column next door). If spatial memory is dictated by the sequential order of objects along a learning path, then we should find that probe distractors are chosen more frequently than the other distractors. Another interesting distractor, not present in the experiment of Thibault et al.

(2013), was also presented for each trial: the same-floor distractor, an object situated in a room on the same floor as the arrival object. In both floor and column learning conditions this object is situated in a room on the same floor as the arrival object (and differs from the probe distractor). The last distractor was chosen so that, among the four objects presented, two were from one floor, and the other two were from another floor. In the floor trials of the column-learning condition only, this object was also a same-column distractor, as it was located on the same column as the correct object.

*Preparation*

Participants attended a pre-experiment session (inspired by Huttenlocher & Presson, 1979) designed to assess whether they had any long-term spatial memory impairment. After the pre-experiment, participants underwent a familiarization phase to acquaint themselves with the main experiment. They experienced a simplified version of the main phase in a smaller virtual environment with four objects in four rooms. Participants experienced the same learning condition they had been assigned for the main experiment.

Performance was not recorded, although feedback on the answers given was provided and, in the event of errors, the trial was repeated.

*Hypothesis*

This work reconsidered the three hypotheses studied by Thibault et al. (2013). We argued that if human spatial memory of multifloored environments (here a cylindrical one) is preferentially exploited by floors regardless of the learning mode, then better performance should be observed for floor trials than for column trials. If the use of spatial memory depends on the learning condition, we should observe better performance for familiar segments compared to novel ones. Finally, if learning spatial relations is easier for floor learners, we should observe better performance for floor learners than for column learners in floor trials as well as in column trials.

## 2. Results

All subjects sat through the whole session completely, without experiencing unusual fatigue or nausea. Performance was computed as the rate of correct object selection in the total number of trials. During the testing phase, each participant went through 8 (4x2) floor trials, 8 (4x2) column trials 4 (2x2) closure and 4 (2x2) misaligned trials, for each type of trial. The two series were pseudo-randomly ordered in order to diminish any precedence effect. The overall mean performance was 57.5% correct answers (SEM = 11), less accurate than in Thibault et al. (2013, 67%). We ran one-sample t-tests to compare performance in each elementary condition and found that all but the performance of floor learners in column recognitions (26%, t(15)=0.1, p=0.92) were significantly above chance level (t(15)>3.8, p<0.01). In floor trials both floor and column learners yielded performances above the chance level (82% and 52% respectively). Table 1 shows the main performances obtained in this experiment.~~, as compared to the ones obtained in the rectilinear experiment of Thibault et al. (2013). However, we do not include a Welch t-test between them because of the difference in the choice of distractors in the testing phase.~~

| Learning condition | Testing condition | ~~Cylindrical~~Performance (% of correct answers) |
|---|---|---|
| Floor | *Floor* | 82 |
| | *Column* | 26 |
| Column | *Floor* | 56 |
| | *Column* | 69 |

Table 1. Performances (%) of learning groups in the ~~in rectilinear (Thibault et al., 2013) and~~ cylindrical building~~s~~

The most striking result is thus the poor, chance level performance of floor learners in novel column trials. Performance and RTs were analyzed using a two-way ANOVA between learning and testing conditions (2x2 levels, see Table 2), seconded by Kruskal-Wallis tests,

more robust to outliers. Firstly, it showed the significant effect that this testing condition has on performance: $F(1, 56) = 7.93$, $p < 0.01$, also confirmed by a Kruskal-Wallis test: $p < 0.05$, $\chi^2 = 6.44$. Indeed, participants performed better in floor trials than in column ones. Secondly, this finding was not significantly dependent on the learning condition: $F(1, 56) = 1.34$, $p = 0.25$, as confirmed by a Kruskal-Wallis test: $p = 0.35$, $\chi^2 = 0.89$. Lastly, we observed an interaction between learning and testing conditions, showing that both groups performed better in familiar than in novel trials: $F(1, 56) = 21$, $p < 0.01$. However, in novel trials alone, column learners performed better than floor learners: Two Kruskal-Wallis tests conducted for separate learning conditions show that, while floor learners performed better in familiar than in novel trials: $p < 0.01$, $\chi^2 = 13.83$, column learners answered equally well in both familiar and novel trials: $p = 0.2$, $\chi^2 = 1.63$ (see Fig. 3a). Column learners also outperformed floor learners in novel trials ($p<0.01$, $\chi^2 = 6.65$).

| Learning condition | Testing condition | | | | | All trials |
|---|---|---|---|---|---|---|
| | *Floor* | *Column* | *Familiar* | *Novel* | *Closure* | |
| Floor learners | 82 (10) | 26 (11) | 82 (10) | 26 (11) | 68 (8) | 54 (11) |
| Column learners | 56 (13) | 69 (12) | 69 (12) | 56 (13) | 43 (9) | 67 (12) |
| All subjects | 67 (11.5) | 47.5 (11.5) | 75.5 (11) | 39 (12) | 55.5 (8.5) | 57.5 (11.5) |

Table 2. Average performances of subjects as a percentage of correct answers (mean, *SEM*)

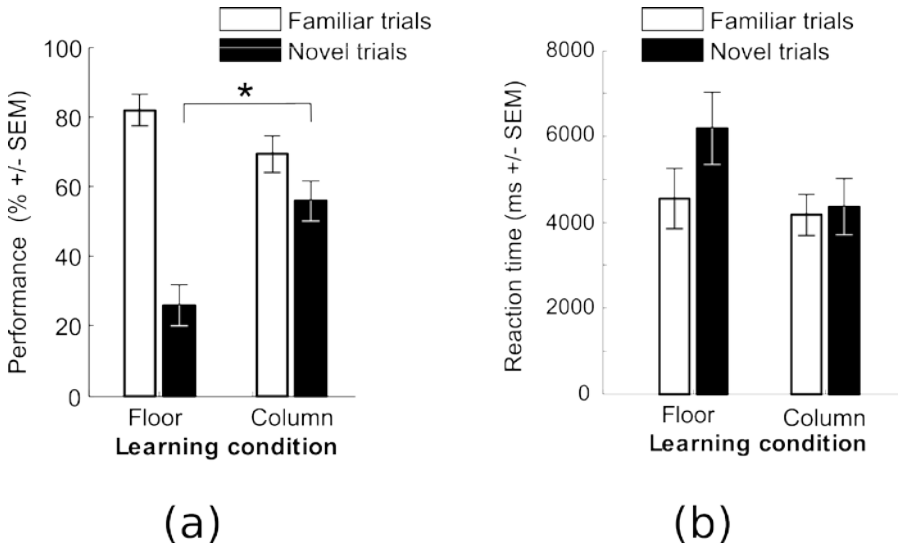



Figure 3. Bar charts of the results. (a) Performance as a function of learning and testing conditions. * the star between black bars emphasizes the significant difference between learning conditions on novel trials. More precisely, column learners outperformed floor learners in novels trials, i.e. column recalls for floor learners and floor recalls for column learners (b) Composition of “same-floor plus correct object” responses in novel trials. (c) Reaction time as a function of learning and testing conditions. The error bars represent SEM.

A trend towards significance was found for performances in closure trials between learning conditions: $F(1, 56) = 3.76$, $p = 0.053$. Both floor and column learners responded better than chance (68% and 43%, $t(15)>1.9$, $p> 0.07$). Mis-categorized trials were answered better than chance (58 % and 60 %, $t(15)>5$, $p<0.01$) and equally well in both floor and column learning conditions (Kruskal-Wallis: $p = 0.84$, $\chi^2 = 0.04$).

In novel trials, distractors were analyzed by comparing their selection rate with the average selection rate. We computed the probability of choosing the probe or the same-floor distractor by chance among the three distractors by following a binomial distribution law B(n,

p) where p = 1/3 (since it is one of three distractors) and n is the number of errors committed (n = 45 for floor learners, n = 30 for column learners). We only include the first occurrence of each trial (as indicated in the methods all trials are doubled during the testing phase) in order to discard any precedence effect. However, we also ran a binomial test with both occurrences of each trial and we got similar results. Floor learners and column learners respectively selected the probe distractor 8 and 9 times. By comparing these values with a two-tailed binomial test for a confidence interval of 95%, we observed that for floor learners the same floor distractor was selected significantly more frequently than the chance level (36 selections, $p<0.01$), while probe and other distractors were chosen less frequently than by chance by floor learners (resp. $p<0.01$ and $p<0.05$). The same method showed that column learners did not choose any distractor more frequently than by chance, including the other distractor, which is also a same column distractor in this very condition ($p=0.8$ for probe, $p=0.12$ for same floor and $p=0.3$ for other/same-column distractors). Binomial tests are summed up on the Table 3.

| Learning condition | *Probe distractor* | *Same floor error* | *Other* |
|---|---|---|---|
| Floor learners | *0.17* [0.20; 0.49] | **0.8** [0.20; 0.49] | *0.02* [0.20; 0.49] |
| Column learners | 0.3 [0.17; 0.52] | 0.46 [0.17; 0.52] | 0.23 [0.17; 0.46] |

Table 3. Computed probability of the observed selections of each distractor, enclosed by the confidence interval at 95 % following the binomial law of choosing each distractor with a probability of 1/3. Values in bold show computed probability greater than chance level; values in italic show computed probability smaller than chance level.

Concerning the RTs, a two-way ANOVA did not show any significant difference between either learning conditions: $F(1, 56) = 2.64$, $p = 0.11$, or testing conditions: $F(1, 56) = 1.15$, $p = 0.29$ (see Table 4 and Fig. 3c).

| | Testing condition | |
|---|---|---|
| Learning condition | *Floor* | *Column* |
| Floor | 4.5 s (0.7) | 6.2 s (0.8) |
| Column | 4.4 s (0.6) | 4.2 s (0.5) |

Table 4: Reaction Times for the different conditions (s) (Mean, *SEM*)

## 3. Discussion

Existing studies on spatial memory in multifloored buildings suggest that people prefer to memorize such environments by floors, and are also influenced by the learning path. Our experiment in a cylindrical multifloored environment expands on these results. We tested floor and column trials in groups that had learned the path either by floors or by columns, and we analyzed how interaction of learning and testing conditions influenced the performance. It significantly showed that the familiarity (floor, resp. column trials for floor, resp. column learners) helped participants to recall connections between objects. However, only column learners could infer the positions of objects in novel, i.e., floor trials, while floor learners were unable to infer connections between vertically-aligned objects.

Floor learners did not only fail to infer the location of objects across floors: In novel trials, while the correct object was not chosen more often than by chance, the same-floor object was chosen more than twice above chance level. During the learning trajectory, the same-floor object was always seen sooner than the correct one. Therefore, floor learners may have used a "floor-sequence" rule: They chose the first object seen on the right floor during the learning phase.

The poor performance of floor learners may be due to the nature of their learning trajectory which is much curvier, and therefore disorientating, than the column-learning trajectory, having a cumulative turn of 720° compared to 240°. Moreover, no reorientation was possible due to the environment’s circular shape. This has already been pointed out by Kelly et al. (2008) in a spatial updating experiment in planar environments, in which

participants walked down a circular path either in a circular, square or trapezoidal room. The pointing error increased with the path length in the circular room, but not in the other rooms (see also Shelton & McNamara, 2001 for a similar observation in a judgment of relative direction task taking place in circular rooms). In our experiment, such a difference in the disorientation caused by the learning path led floor learners to memorize only the relative location of objects within a floor, and not across floors, while column learners, less disoriented, succeeded in memorizing the relative location of objects both within floors and across floors.

~~The same order of preference for the distractors in novel trials (a large preference for the same-floor distractor, but not for the probe distractor) reinforces the idea that the same primary grouping by floors was at work in both groups. However, column learners were more favoured than floor learners on connecting objects across floors.~~

The great preference of floor learners in novel trials (table 3) as well as the good performance of columns learners in familiar tr~~a~~ials suggest that a primary grouping by floors was at work in both groups.

Furthermore, familiarity did not yield faster reaction times – generally longer than in Thibault et al. (2013) and Wolbers and Büchel (2005) – for both learning groups. In addition, in these trials, floor learners chose the same-floor object much more frequently than the correct one.

Our results complete those of the experiment conducted by Thibault et al. (2013, see Table 1) in which the materials and the methods were almost identical, excepted for the shape of the environment, suggesting that memorization of a cylindrical multifloored building is done by floors. In addition to the familiarity effect, both groups preferred correct and same-floor objects, and thus organized the building by floors. This was not demonstrated in the

rectilinear experiment because the building was likely handled like it was a two dimensions frontal environment, but this is in line with neurophysiological studies suggesting that neural bases handling navigation memorize 3D space as a stack of 2D plans. For instance, Hayman et al. (2011) showed that hippocampal place cells from rats respond more accurately in horizontal dimensions than in vertical dimensions, as if several 2D maps of the environment were stacked. Therefore, a circular path seems to engage a memory of a horizontal plane whereas a rectilinear path may engage a memory of a one-directional space as in Thibault et al. (2013). The relatively good performance of both ~~the~~ column learners~~, and especially the~~ floor learners~~,~~ in closure trials (respectively 68 % and 43 % of correct answers, both responded better than chance) suggest that participants were able to take advantage of the circular organization of floors.

However we did not test every segment, like diagonal one, in which the participant would be moved simultaneously by floor and by column. Those segments would allow us to better characterize how participants have memorized the environment according to their learning condition. In addition, since our experiment did not involve any actual navigation, we need to extend these findings with a protocol in which participants are free to find their way in buildings exhibiting rectangular or circular 2D floors.

While uncommon, there are cylindrical buildings in the world, such as the “Maison de la Radio” or “Charles de Gaulle terminal 1 airport” in Paris or coming Apple headquarter in Cupertino, but also industrial structures such as power plants. For instance, our results can have practical uses for workers who must deal with vertically aligned targets like scaffoldings in offshore platforms or in electric stations: They could benefit from a visit favouring vertical trajectories when discovering these installations.

Our results (see Figure 3) show that, in contrast to a rectilinear environment, a cylindrical environment is better memorized by floors regardless of the learning mode. But only participants who learnt it by columns could also memorize it by columns. Taken together, this work and that of Thibault et al (2013) show that spatial memory of multifloored environments results from an interplay between the learning mode and the environment's structure.

## References

[1] Büchner, S., Hölscher, C., & Strube, G. (2007). Path choice heuristics for navigation related to mental representations of a building. *Proceedings of the Euro CogSci 2007*, 504-509.

[2] Christou, C., & Bülthoff, H. (1999). View dependence in scene recognition after active learning. *Memory & Cognition*, 27 (6), 996-1007.

[3] Hayman, R., Verriotis, M., Jovalekic, A., Fenton, A., & Jeffery, K. (2011). Anisotropic encoding of three-dimensional space by place cells and grid cells. *Nature Neuroscience*, 14 (9), 1182-1188.

[4] Hölscher, Meilinger, Vrachliotis, Brösamle, & Knauff (2006). Up the down staircase: Wayfinding strategies in multi-level buildings. Journal of Environmental Psychology, 26(4), 284-299.

[5] Huttenlocher, J., & Presson, C. (1979). The coding and transformation of spatial information. *Cognitive Psychology*, 11 (3), 375-394.

[6] Jeffery, K., Jovalekic, A., Verriotis, M., & Hayman, R. (In press). Navigating in a 3d world. *Behavioral and Brain Sciences*.

[7] Kelly, J., McNamara, T., Bodenheimer, B., & Carr, T. (2008). The shape of human navigation: How environmental geometry is used in maintenance of spatial orientation. *Cognition*, 109(2), 281–286.

[8] Knierim, J. & Hamilton, D. (2011). Framing spatial cognition: neural representations of proximal and distal frames of reference and their roles in navigation. *Physiological Reviews*, 91(4), 1245-1279.

[9] Montello, D., & Pick, H. (1993). Integrating knowledge of vertically aligned large-scale spaces. *Environment and Behavior* , 25 (3), 457.

[10] Shelton, A., & McNamara, T. (2001). Systems of spatial reference in human memory. *Cognitive Psychology*, 43 (4), 274-310.

[11] Thibault, G., Pasqualotto, A., Vidal, M., Droulez, J., & Berthoz, A. (2013). How does horizontal and vertical navigation influence spatial memory of multifloored environments? *Attention, Perception, & Psychophysics*, 75 (1), 10-15.

[12] Wilson, P. N., Foreman, N., Stanton, D., & Duffy, H. (2004, March). Memory for targets in a multilevel simulated environment: evidence for vertical asymmetry in spatial memory. *Memory & cognition*, 32 (2), 283-97.

[13] Wolbers, T., & Buchel, C. (2005). Dissociable retrosplenial and hippocampal contributions to successful formation of survey representations. *Journal of Neuroscience*, 25 (13), 3333