Cognitive Processing (2021) 22:501–514
https://doi.org/10.1007/s10339-021-01022-9

RESEARCH ARTICLE

The art gallery maze: a novel tool to assess human navigational abilities

Hamed Taheri Gorji[1,2] · **Michela Leocadi**[1,3] · **Francesco Grassi**[1] · **Gaspare Galati**[1,2]

Received: 10 August 2020 / Accepted: 21 February 2021 / Published online: 1 April 2021

Abstract
Humans differ widely in their ability to navigate effectively through the environment and in spatial memory skills. Navigation in the environment requires the analysis of many spatial cues, the construction of internal representations, and the use of various strategies. We present a novel tool to assess individual differences in human navigation, consisting of a virtual radial-arm maze presented as an art gallery to explore whether different sets of instructions (intentional or incidental) affect subjects' navigation performance. We furthermore tested the effect of the instructions on exploration strategies during both place learning and recall. We evaluated way-finding ability in 42 subjects, and individual differences in navigation were assessed through the analysis of navigational paths, which permitted the isolation and definition of a few strategies adopted by the incidental and intentional instructions groups. Our results showed that the intentional instruction group performed better than the other group: these subjects correctly paired each central statue and the two paintings in the adjacent arms, and they made less working and reference memory errors. Our analysis of path lengths showed that the intentional instruction group spent more time in the maze (thus being slower), specifically in the central hall, and covered more distance; the time spent in the main hall was, therefore, indicative of the quality of the following performance. Studying how environmental representations and the relative navigational strategies vary among "intentional" and "incidental" groups provides a new window into the acknowledgment of possible strategies to help subjects construct more efficient approaches in human navigation.

Keywords Spatial navigation · 6-arm Radial maze · Intentional and incidental instructions · Navigational strategies · Art gallery maze

Introduction

Individual differences in cognitive abilities are a hallmark of human evolution (Thornton and Lukas 2012), and people differ widely in many aspects of their lives, such as intelligence, visual acuity, sound discrimination, eloquence, and social skills (Williams, Myerson and Hale 2008). Accordingly, it is not surprising that there is also variability in the ability to navigate effectively through the environment (Wolbers and Hegarty 2010) and in spatial memory skills. Navigation in both real and virtual environments requires the analysis of many spatial cues and landmarks, which can be examined in different ways, depending on the internal representation of the environment (Edward C Tolman 1948). Different representations lead to the construction of various spontaneous strategies that people adopt to orient and explore new settings (Edward Chace Tolman and Honzik 1930): some strategies can be adaptive to reach a final destination, while others can induce navigators to lose themselves upon their surroundings (Dabbs Jr, Chang, Strong and Milun 1998).

Mazes are the most common tool used in tasks examining navigational behavior in animals; they are versatile because they can measure both navigational performance and strategy selection (Astur, Tropp, Sava, Constable and Markus 2004; Jacobs, Thomas, Laurance and Nadel 1998), and they

---

✉ Hamed Taheri Gorji
hamed.taherigorji@uniroma1.it

[1] Department of Psychology, Sapienza University of Rome, Rome, Italy

[2] Cognitive and Motor Rehabilitation and Neuroimaging Unit, Santa Lucia Foundation (IRCCS Fondazione Santa Lucia), Rome, Italy

[3] Neuroimaging Research Unit, Institute of Experimental Neurology, Division of Neuroscience, San Raffaele Scientific Institute, Vita-Salute San Raffaele University, Via Olgettina, 60, 20132 Milan, Italy

are a very challenging task for both rodents and humans, since they employ a variety of mnemonic processes, which encompass the acquisition and spatial localization of relevant visual cues that are processed, consolidated, retained, and then retrieved to successfully navigate in the environment. The Radial Arm Maze, the Morris Water Maze, the Y-maze, and others represent today the gold-standard for rodent research in the field (Hodges 1996). Variations of these mazes have been employed in human research as well and usually consist of PC-rendered environments, in which subjects can navigate using a mouse, keyboard, and other peripherals (Ruddle, Payne and Jones 1997). In recent times, the employment of virtual-reality setups has achieved increasing popularity due to more powerful and cheaper devices (Kelly and Gibson 2007). Furthermore, literature is not void of successful attempts with full-scale mazes for real-life human navigation (Bischof and Boulanger 2003; Bohbot, Copara, Gotman and Ekstrom 2017; Spriggs, Kirk and Skelton 2018; Wood et al. 2018). The use of mazes to study human navigation strategies has become wider in the last years, since these tools can replicate navigational tasks that humans perform every day, such as going to work, reaching a certain place, but every day navigation usually happen in several contexts, varying in time course, familiarity, and environmental complexity. A move toward increasing ecological validity has been the employment of virtual-reality technology to simulate real-world scenarios (Shelton and Gabrieli 2002; Spiers and Maguire 2006), which consent flexible adaptation and manipulability of the simulated environment (Kearns and Moon 2002).

Different mazes can be employed to address specific aspects of spatial navigation, and protocols vary from one study to another depending on the specific experimental question. Despite this variability, the vast majority of maze-based experiments are designed to measure subjects' performance in a task. Usually, performance is simply measured as the number of errors or latency during navigation in the environment (Kim et al. 2018; Levy et al. 2005; Walkowiak et al. 2015). Nevertheless, analyzing behavior more deeply can lead to a better understanding of human behavior and exploration strategies during spatial navigation. As a matter of fact, people can behave in such different ways while navigating the same environment: some may prefer to navigate longer in open portions of the environment to access a broader range of spatial information, some others may instead travel in straight paths between different reference landmarks; some may maintain an average high-speed during navigation, some others may stop and change their direction more frequently (Newcombe 2018; Ugwitz et al. 2019).

Moreover, previous studies illustrated that human subjects facing a virtual environment usually use one of the "spatial strategy" or "response strategy" as a navigational strategy (Iaria, Petrides, Dagher, Pike, and Bohbot 2003; Konishi and Bohbot 2013). Spatial memory, or the "spatial strategy," is one of two navigation strategies that can be used when going somewhere. It involves navigating within an environment by forming relationships between different landmarks and orientating oneself in relation to those landmarks. This strategy can lead to creating a cognitive map and a mental representation of an environment (McNamara 1986). On the other hand, in the "response strategy" subjects by learning a series of stimulus–response associations like taking a right or left from a given starting position can orient themselves in an environment (Konishi et al. 2016).

Distances, time, speed, direction changes, and favorite portions of the environment are all examples of behavioral features that characterize human navigational performance. We believe that the study of human navigational abilities would achieve a more profound insight on individual differences, with the focus of attention extended from the usually investigated navigation measures, such as overall time, velocity, and distance to more defined and specific behavioral outcomes of navigation, their variability among people, and how they are influenced by environmental and experimental conditions.

To this end, we developed a new virtual environment, which we called the *art gallery maze*, consisting of an art gallery with a distinctive geometry and a specially selected set of artworks and statues potentially suited as landmarks. Subjects can navigate without constraints while attempting different tests of spatial learning and recall, and the experimenter can extract not only performance indexes but also a set of behavioral features of navigation. To test the usefulness of such a novel tool, we applied it to the study of a particularly interesting and well-documented aspect of human navigation: the effect of different sets of learning instructions.

When human individuals navigate in the environment, they encode all the surrounding stimuli, and then different learning strategies are applied. If the subjects are not intentionally paying attention to their surroundings, their learning process would be 'incidental,' while, on the contrary, they would intentionally memorize the environment. Incidental learning refers to an unconscious manner for knowledge acquisition that individuals are not aware of and that they cannot even verbalize. In contrast, individuals adopt intentional learning when they gain knowledge in a conscious way, as they attempt to obtain such information declaratively (DeKeyser 2008; Stadler 1997). According to the type of learning experience that the individuals would perform, incidental or rather intentional memories would be retrieved. The type of instructions that subjects are given might alter their navigation experience and therefore affect the quality of the acquired information: when given intentional instructions (which induce an intentional learning strategy), subjects tend to improve the quality of the learning process, leading to a better performance in the navigational task; on the other hand, if an incidental learning experience is induced, the retrieval stage would be affected.

Van Asselen et al. (2006) investigated the influence of intentional and incidental learning conditions on route learning in two groups of participants. Participants in the first group were asked to pay attention to the route, while participants in the second passed through the route without paying attention. The 'intentional group' performed significantly better than the 'incidental group' on map drawing and navigational tasks. In addition, the intentional group estimated the route length to be higher than the real value, while, on the contrary, the incidental group estimated the path length to be shorter. Moreover, the two groups showed no difference when asked to recognize and order landmarks (van Asselen, Fritschy and Postma 2006).

We, therefore, tested two groups of subjects in our task, asking them to navigate the art gallery maze several times. One group was provided with intentional instructions to learn and memorize the environment and the positions of the objects, while the other group visited the maze in order to eventually give their opinion about the artworks presented (incidental instruction group). Both groups underwent a place learning task where they learned the position of novel objects that were not present during the initial exploration. Our hypothesis is that, given 'intentional instructions,' participants would perform better both in terms of exploration strategies, the number of errors and in re-creating the cognitive map of the environment; furthermore, we would expect that a different set of instruction would affect exploration strategies both during the learning process and during recall. We believe that the novelty of our investigation compared to previous studies resides in the collection of a series of behavioral measures and the analysis of path lengths, which could help us identify specific navigational strategies in our cohort.

Materials and methods

Subjects

A total of 42 university students (23 females) were recruited at Sapienza University of Rome. Subjects were randomly assigned to two different groups. 21 subjects received Intentional instructions (13 females) vs. 21 subjects received Incidental instructions (10 females). The mean age among all the participants was 24.47 (SD = 2.49). All subjects were healthy, and nobody reported any mental or psychiatric disorders. They were all Italian mother-tongue and had a normal or corrected vision. Each participant gave written informed consent for participation in the study and for personal information treatment. The materials and the methods of the experiment were approved by the Technical University of Berlin Research Ethical Committee.

The art gallery maze

A virtual-reality environment was designed as to have the shape of a radial-arm maze and was built with the open-source software Maze Suite (v. 3.0.1, www.mazesuite.com), created by Hasan Ayaz and colleagues (Ayaz et al. 2008, 2011). Maze Suite facilitates the creation and visualization of a 3D environment and is constituted by a complete set of tools that allows researchers to perform motor control, spatial, and navigational behavior experiments within interactive and extendable 3D virtual environments.

Our maze was conceived as an art gallery, which was constituted by a hexagonal central room from which six different arms extended outwards symmetrically (Fig. 1). The symmetry was maintained to avoid confusion or even facilitate effects during the tasks, and to make the environment as homogeneous as possible. This type of maze is commonly used in rodent studies because it is a useful tool to study both reference and working memory and their characteristics (Olton and Samuelson 1976).

Even though radial-arm mazes can be created with more than six arms to make the tasks more complicated, for being our experiment merely explorative, we wanted to create an environment with a medium difficulty level. Each arm of our maze was enriched by two lateral enlargements, one at the mid-point in length and on the left side, the other at the end of the corridor, and on the right side (Fig. 1).

The maze was furnished in a way to make it like a real art gallery, with artworks exposed in all parts of the museum. Since the museum had a hexagonal central hall, three big statues to be potentially used as landmarks were inserted along its perimeter, each one in the middle position between the two neighboring corridors (Fig. 1). Their position was accurately chosen so that each stimulus was equidistant from the other two and from the entrance of the two neighboring corridors; for geometrical reasons, the three central stimuli were inserted as if they were the vertices of a regular triangle. Other artworks were exposed in each of the two lateral enlargements along the corridors. The lateral enlargements at the end of the corridors contained six different statues, while the middle six lateral enlargements of the corridors contained six paintings hung on the wall. We chose to create a cloudy skybox and to leave the museum open without a ceiling to avoid a narrow and claustrophobic setting.

For the paintings, we thought the best choice would be to omit famous and widely known paintings to avoid the subjects could remember or already know the different stimuli, and we focused our choice on some paintings from the National Gallery of Art (https://www.nga.gov/), which mostly convey neutral emotional values. On the other hand,

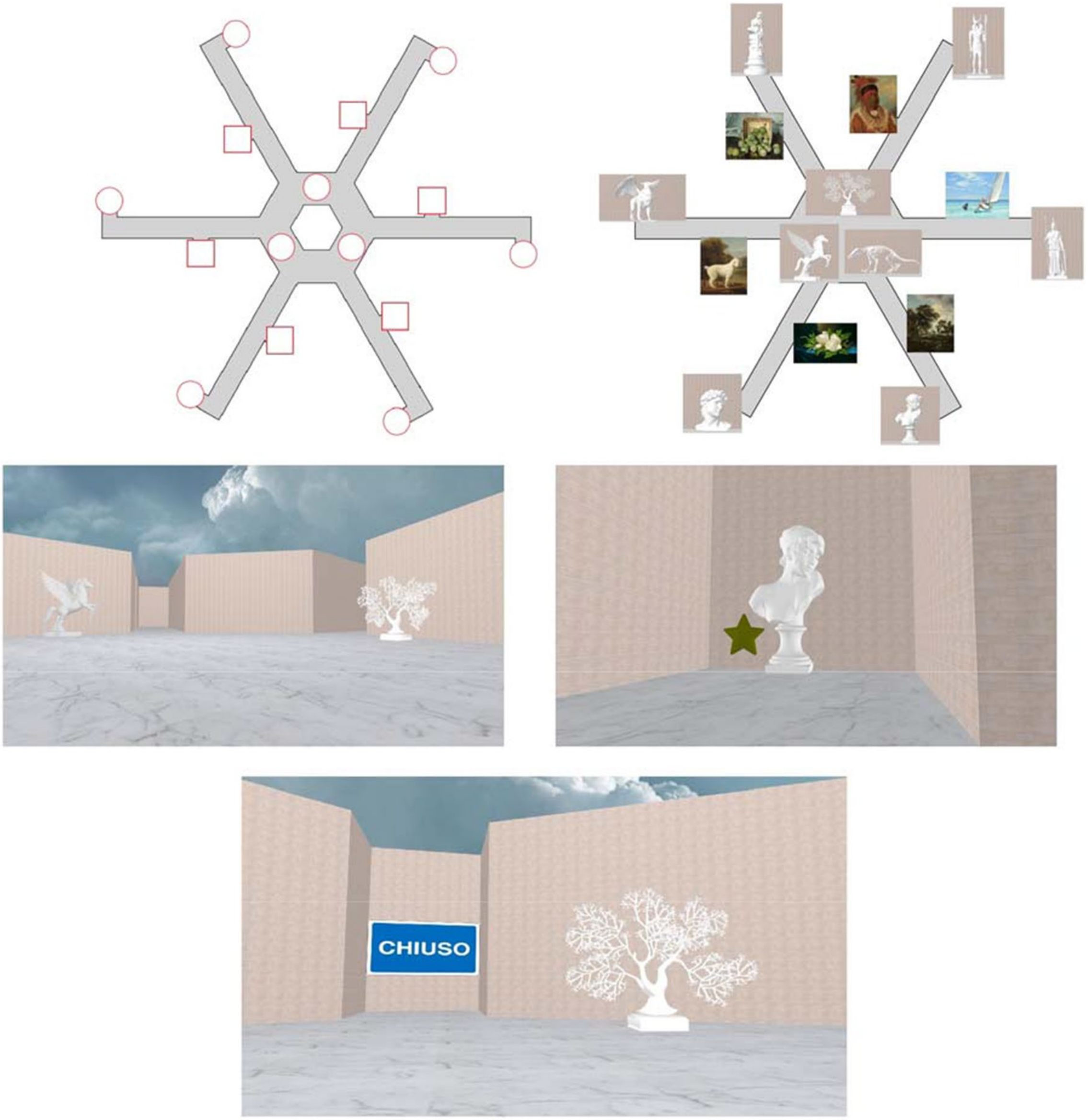

Fig. 1 Top. Maze map and positions of the artworks inside the maze. Middle. Images of the art gallery. The picture on the left depicts the hexagonal hall of the museum, while the one on the right represents the end of a corridor with a star. Bottom. Picture of one of the three walls with the “Closed” sign (‘Chius so’ in Italian)

we selected the nine statues (six to be positioned in the arms and three in the central room) from a wide sample of 3D objects freely available on the internet (in our case, from the website Archive 3D—ww.archive3d.net). Given that the original objects from the website were not uniformly and similarly colored, and they presented different shades and dimensions, we made them all white, equally sized, and as homogeneous as possible.

We selected artworks that would be equal in terms of salience and pleasantness for our participants, in order to avoid that the characteristics of the stimuli could affect the behavioral performance. To select the most suitable artworks for this purpose, an online questionnaire was created, in order to collect evaluations about salience and pleasantness among a wide range of possible alternatives. The artworks eventually chosen for the experiment were the ones which obtained a similar evaluation in both categories.

The different positions and pairings between paintings and statues were randomized. Figure 1 shows a schematic representation of the final positions of the artworks inside the maze (Top), as well as some samples of the environment as it was perceived by the experimental participants (Middle and Bottom).

Apparatus

The entire experiment was performed in the Brain Imaging Laboratory of the Department of Psychology at "La Sapienza" University of Rome. The virtual-reality environment was presented to our subjects on a computer screen located in one room of our laboratory; the computer was equipped with a keyboard, and subjects were asked to use only the four arrow keys to move (forward, backward, left and right) in the setting. A mouse was provided too, and it was used to change direction while moving in the environment, like turning left or right. Moreover, all subjects were asked regarding their familiarity with playing video games by utilizing the keyboard and mouse, and also, they were informed that walking through the art gallery maze is the same as a first-person perspective video game. A simple training phase was designed for the subjects who did not have any video game playing experience to get familiar with using mouse and keyboard.

Subjects were always sat comfortably on a chair positioned at the same distance in front of the computer screen, and the light was maintained on in order to allow everyone to both reads and listen to the instructions written on an A4-format blank paper sheet. During task performance, the light was switched off to facilitate the vision of the virtual-reality environment on the computer screen.

Experimental procedure

Self-report measures

The day before the experiment, participants completed the "Santa Barbara Sense of Direction Scale" (SBSOD) questionnaire (Hegarty, Richardson, Montello, Lovelace, and Subbiah 2002), a self-report tool assessing spatial environmental abilities, which include the subjective assessment of the sense of direction (SOD), a good objective predictive factor of various spatial skills. When people are asked to judge their SOD as "good" or "bad," they are basing their judgment on environmental tasks such as wayfinding paradigms, using maps for orientation, and giving and receiving route indications. The SBSOD is composed of 15 items that subjects should rate from 1 to 7 (with 1 = I completely agree and 7 = I completely disagree). The questions are focused on the assessment of the personal spatial and navigational abilities, on personal preferences and experiences. We reported SBSOD scores for the two experimental groups in Table 1.

Familiarization phase

In the familiarization phase, subjects sat in front of the computer screen, were informed of the opportunity to visit a virtual art gallery with some exposed artworks, and received either "intentional" or "incidental" instructions according to their group. Intentional instructions were the following: "You should move freely in the gallery and appreciate all the artworks that you will see. You have ten minutes time to do so and to remember the position of the artworks in the corridors. You will be asked a few questions about the gallery; thus, it is really important that you pay attention to all details". Incidental instructions were the following: "You should move freely in the gallery and appreciate all the artworks that you will see. You have ten minutes time to do so. We will eventually ask your opinion about the artworks presented." Both groups were also instructed to press the ESC button when done or the program will automatically be closed if the time is over.

Environmental knowledge test

Immediately after familiarization, subjects were presented a series of 9 multiple-choice questions:

1. What is the shape of the central room of the museum?
2. How many statues are there in the central hall?
3. How many statues are there in the museum?
4. How many paintings are there in the gallery?
5. How many corridors extend from the central hall of the gallery?
6. How many artworks did you see in each corridor of the gallery?

Table 1 Comparison of the navigational performance scores (intentional instruction vs. incidental instruction groups)

	Intentional mean	Incidental mean	*P*-value
Santa barbara sense of direction questionnaire	58.09	61.90	0.406
Environmental knowledge questionnaire	7.95	7.04	0.391
Artworks recognition questionnaire	47.85	46.71	0.213
Statues order	72.22	72.35	0.858
Paintings order	76.98	67.46	0.074
Statues to central	74.07	76.45	0.750
Paintings to central	79.62	64.55	0.009
Arm pairing	60.31	28.57	0.002

7. On which side of the corridor are the paintings exposed, left or right?
8. On which side of the corridor are the statues exposed, left or right?
9. The statues present in the central hall constitute the vertices of a geometrical figure: which one?

Each question, except for questions number 7 and 8, had five total multiple-choices answers. Answers to questions 7 and 8 could be "left" or "right." For question number 6, it was clarified that the term "artworks" meant both statues and paintings considered together. For each correct answer, a score equal to 1 was attributed, whereas each wrong answer was scored with 0. The final score was the sum of all the correct answers (9 Scores).

Artworks recognition test

Immediately afterward, participants performed a recognition task where they were asked, for each of a series of paintings and statues consecutively presented on the computer screen, whether they were present in the previously visited art gallery or not. Stimuli included the 6 paintings and 9 statues presented in the gallery, and further 14 paintings by National Gallery of Art and 21 more statues similar to those selected for the gallery, each presented alone in front of a wall. We randomized the order of items. Each correct answer was scored with 1, while each error was scored with 0. The final score is given by the sum of all the correct answers in both sections (paintings and statues, 50 scores).

Place learning task

After the completion of the questionnaires, subjects performed a place learning task which allowed the assessment of their ability to memorize, distinguish, information retrieving, and process during the maze exploration. To this end, similar to food reward in animal studies (Dubreuil, Tixier, Dutrieux, and Edeline 2003; Goodrich-Hunsaker and Hopkins 2010; Tarragon et al. 2012), four golden stars were positioned at the end of four different arms (see Fig. 1 middle right). Subjects were informed of the presence of some stars and the end of some corridors, but the number and the position of the stars were not informed. Both groups were asked to retrieve all stars and press the ESC button when done, but the intentional instructions group was also asked to try to remember the position of the stars for the following experimental phase. Exploration started as usual from the center of the gallery. The rationale of this task was to give the subjects the opportunity to explore, learn, and memorize the different spatial position of the golden stars, which could lead to extensively investigate subjects' spatial working and reference memory in the test phase. The reference memory can be assessed when subjects only visit the arms which contain the golden stars, and visiting the arms without golden stars results in reference memory errors. In the same way, the working memory can be assessed when subjects enter the arms with the golden star once and double-entry into those arms results in working memory error. Reference and working memory errors can be considered as two main dependent variables that characterize the subjects' performance on a radial arm maze (Kassa et al. 2015).

Test phases

Immediately after the learning phase, three further tests were administered.

Star retrieval: subjects were placed back to the center of the gallery and were told that the stars had been placed into the same positions as before, and they had to retrieve them as fast as possible, and without making errors. The perspective from which the exploration of the environment began changed for each subject.

Closed arms trial: subjects were placed back to the center of the gallery and were told that the stars had been placed again into the same positions as before. However, three out of the six corridors were closed with a wall, and a sign reporting the word "CLOSED" on it (in Italian, "CHIUSO"—see Fig. 1 Bottom). Subjects were told there were some restoration works ongoing, and some parts of the gallery were closed, but they had to retrieve all stars in the open corridors as fast as possible, and without making errors. In this phase, there was actually only two reachable stars since the other two corridors containing a star were closed.

Open-arms trial: participants were brought back to the original version of the gallery and told that the restoration works had finished and that they should retrieve the remaining stars, i.e., the stars that they were not able to reach before because of the closed arms. Subjects had to retrieve only two stars in this trial, and the star eventually caught in the closed arms trial was not placed back to its place.

Map completion test

Subjects were then given a blank map of the environment and a series of colored figurines of the different artworks that were presented during the procedure. They were asked to position all the figurines with paintings and statues on the map of the gallery, trying to replicate the position of the artworks and to correctly pair each painting with the corresponding statue.

Since 15 positions were prefixed for the artworks, the map correction could be done from any of these points of view. However, the establishment of a unique correction method was very difficult and intriguing; in fact, due to the enormous number of possible combinations, it was nearly impossible to combine different criteria for a correct and extendible correction method. Here we propose a specific correction method based on some mathematical assumptions. Our map accuracy index is the sum of the five different sub-scores, each accounting for a different aspect of the task requirements. The sum of the five distinct scores gives the final total score. For a more detailed explanation of this unique correction method, please refer to Appendix 2.

The shape of the environment and the disposition of all elements enabled us to isolate five main characteristics, which represent five possible distinct scores. We furthermore distinguished the different artworks based on their location in the museum: central statues (in the hall), paintings, and statues in the arms (external position). The five scores account for five aspects relative to the correct completion of the map.

Debriefing phase

After the Map completion test, subjects were briefly illustrated the rationale of the experiment and the variables of interest. Furthermore, few more questions were asked, such as: "What do you think about your performance? / Did you adopt any strategy during the exploration of the environment? / Did you try to memorize and remember the position of the various artworks according to the different corridors of the gallery." Answers were collected in a qualitative fashion.

Performance scores

We collected performance scores from each subject's behavior:

- score at the environmental knowledge test, assessing learning of the general structure of the environment after the familiarization phase.
- score at the artwork recognition test, assessing memory for landmarks.
- map accuracy indexes, assessing the cognitive map of the environment.

Furthermore, separately for the star retrieval, closed arms, and open arms tasks, we computed the number of committed errors by distinguishing different error types:

1. reference memory errors: number of explored arms not containing a star.
2. corrected reference memory errors: number of times subjects entered an arm not containing a star but then decided to come back to the hall before reaching the endpoint.
3. working memory errors: number of times subject visited again an arm already visited in the same trial, irrespective of whether that arm was contained a star or not.
4. corrected working memory errors: as above, but without reaching the endpoint.

Path analysis

For each of the maze trials (familiarization, learning, and the three test trials), the path covered by each participant was saved to a text file by Maze Suite and contained the coordinates of the position and the orientation of the participant in each moment of navigation. We used this file as the input of our custom MATLAB code to compute a set of behavioral parameters.

The analysis started by subdividing each trial into segments where the subject is located either in the central hexagonal hall or in one of the six arms. Since the subject starts exploration from the central hall and must return to the hall when coming back from one arm before exploring the next one, this subdivision produces a list of segments, where odd segments are near the farthest point was used to distinguish the forward and the backward segment. We had to make sure that the subject stopped and did it close in time to when he reached the destination points.

In fact, some very fast subjects do not stop at all even when picked up the star. The program was also able to determine whether the target was picked up or not, by taking into consideration the farthest position visited within the arm. The exploration of the central hall was split into *steady* and *moving* segments of activity, and then it was further split based on which arm the subject was directed toward. In fact, each time the subject turns while walking and points at a different arm, a new segment was created for the analysis. To make things easier for the analysis, the hall was divided into six slices corresponding to the six arms; in this way, it was possible to determine which arm the subject was facing at. Based on the division of the hall in six slices, it was possible to simply determine when the subject changed his mind; in fact, when he crossed the intersection line between two neighboring slices, it meant that he was going toward another arm which was different from the previously chosen.

The program then reorganized the segments by joining each forward portion of an arm visit with the last part of each hall exploration, where the subject was already directed toward that arm; and by joining each backward portion from an arm to the immediately following arm exploration segment, until the first direction change. Based on this subdivision, we computed a set of behavioral parameters that best characterized the exploration pattern during each phase. Some computed parameters referred to the behavior of the subject in the whole trial, such as the total time spent in the maze and the total visits. Other parameters were computed only in the period spent by the subject in the central hall, after excluding the path segments directed from the hall toward one arm, and back from the arm into the hall. These remaining time periods are best characterized as *decision periods* and were further subdivided into stop and walk periods. These periods were very interesting for our analysis because they reflected subjects' thinking about strategies and their following steps to complete the task. The resulting set of behavioral variables recorded during each phase of the virtual navigation is listed below:

- total time: total time spent in the maze
- time stopped in hall: time spent in the hall without walking
- time walking in hall: time spent in the hall during walking
- distance in hall: total amount of distance covered in the hall
- number of stops in hall: number of stops the subject stops in hall
- cumulative turn when stopped in hall: cumulative angular distance covered while not walking in hall (i.e., looking around).
- time stopped in arm: time spent in the arm without walking
- time moving to target: time spent in arm when subject move toward target
- time moving back from target: time spent in arm when subject back from target
- number of stops in arm: number of stops the subject stops in arm
- cumulative turn when stopped in arm: cumulative angular distance covered while not walking in arm (i.e., looking around).

It is worth mentioning that all time and distance-related behavioral variables are reported in second and meter, respectively.

Results

Between-group analysis

First, we performed a test to check whether our data followed a normal distribution. Since some of our variables were not normally distributed, we analyzed the data with non-parametric statistical tests. Specifically, we performed a two-sample Wilcoxon signed-rank test for analyzing subject's navigational abilities and behavioral variables between Intentional instruction group and Incidental instruction group. The analysis was performed using MATLAB (2017b).

Navigational Performance Scores

To assess whether the type of instruction given (Incidental vs. Intentional) had any impact on subjects' score performances, we performed a Wilcoxon signed-rank test between the two groups for each behavioral variable. As shown in Table 1, results indicate that the mean in the two groups is not statistically significant for the Environmental knowledge questionnaire and artworks recognition questionnaire. For the map questionnaire sub-scores, there are no significant differences in statue order, painting order, and statue to central between intentional and incidental groups, but painting to central score in intentional group with an average of 79.62 is significantly higher than the incidental group with an average of 64.55. Also, there is a significant difference in arm pairing between the intentional group (average = 60.31) and the incidental group (average = 28.57).

Table 2 reports the results relative to the analysis of the number of errors

Table 2 Comparison of subject's errors in the three test trials (Intentional instruction vs. Incidental instruction groups)

	Star retrieval trial			Closed arms trial			Opened arms trial		
	Mean intentional	Mean incidental	*p*-value	Mean intentional	Median incidental	*p*-value	Mean intentional	Mean incidental	*p*-value
Working memory errors	0	0.95	0.004	0.09	1.19	0.041	0.04	0.33	0.288
Reference memory errors	0.38	1.19	0.002	0.19	0.80	0.001	0.28	0.71	0.116
Corrected working memory errors	0.04	0.04	1	0	0.14	0.340	0.19	0	0.340
Corrected reference memory error	0.09	0	0.340	0.09	0.14	0.653	0.09	0.09	0.612

Wilcoxon signed-rank test indicated that the mean of the working memory errors and reference memory errors in the incidental group were significantly higher than the ones of the intentional group for the first and the second trial of the test phase. Moreover, we couldn't find any significant difference in corrected errors for all test phase trials

Behavioral variables

Familiarization phase

As shown in Table 3 during familiarization, those subjects provided with intentional instructions (as it was expected based on the instruction) spent more time in the maze, and they also covered a longer distance in the central hall compared to the other group. The results also show that the subjects of the intentional group tend to spend more time and traverse more distance in the central hall and in the arms of the art gallery as opposed to the other group. The significant differences between the cumulative turns when the subjects stopped in the hall and arms indicate that the intentional group evidently explored the environment paying more attention than the incidental group.

Learning phase

During the learning phase (Table 3), the Intentional instruction group spent more time in the environment, with an average time of 223.59, and subjects were in general, slower, compared to Incidental group's participants, with an average time of 155.40. Moreover, Wilcoxon signed-rank test showed that the intentional group spent more time while stopped in the central hall and in the arms with an average time of 40.27 and 59.53, respectively, compared to the incidental instruction group with an average time of 18.93 for the time stopped in the hall and 28.12 for the time stopped in the arms.

Test trials

In the star retrieval and closed arm trials (Table 4, left and right column, respectively), subjects who received

Table 3 Subject's behavior during familiarization and learning phases

	Familiarization phase			Learning phase		
	Mean intentional	Mean incidental	*p*-value	Mean intentional	Mean incidental	*p*-value
Total time	527.53	309.45	< 0.001	223.59	155.40	0.030
Time stopped in hall	125.31	60.48	< 0.001	40.27	18.93	0.010
Time walking in hall	29.60	21.76	0.009	11.76	9.44	0.406
Distance in hall	168.07	127.04	0.012	67.10	54.03	0.314
Number of stops in hall	45.61	26.95	0.001	17.80	1.04	0.069
Cumulative turn when stopped in hall	6775	3394	< 0.001	2107	1218	0.062
Time stopped in arm	193.41	102.59	0.003	59.53	28.12	0.015
Time moving to target	–	–	–	57.96	50.53	0.314
Time moving back from target	–	–	–	54.04	48.36	0.497
Number of stops in arm	92.23	55.23	< 0.001	41.14	30.23	0.054
Cumulative turn when stopped in arm	9080	5407	0.002	3904	3028	0.208

Table 4 Subject's behavior during test phases

	Star retrieval			Closed arms trial			Opened arms trial		
	Mean intentional	Mean incidental	*p*-value	Mean intentional	Mean incidental	*p*-value	Mean intentional	Mean incidental	*p*-value
Total-time	75.89	77.31	0.949	56.78	69.55	0.352	67.57	58.01	0.919
Time stopped in hall	15.45	4.25	0.002	23.36	14.92	0.0442	28.62	12.69	0.113
Time walking in hall	4.35	6.73	0.110	2.64	6.03	0.0381	2.41	4.53	0.0519
Distance in hall	24.96	39.52	0.110	15.84	35.19	0.002	13.91	26.25	0.0519
Number of stops in hall	7.38	3.80	0.040	5.04	5.57	0.759	6	4.09	0.949
Cumulative turn when stopped in hall	594.76	222.23	0.008	1041	943.2	0.137	970.89	575.42	0.392
Time stopped in arm	12.20	6.17	0.026	5.95	5.05	0.158	8.98	5.53	0.322
Time moving to target	24.44	30.87	0.041	14.18	23.96	0.002	15.90	19.02	0.465
Time moving back from target	19.45	29.29	0.034	10.65	19.59	0.008	11.66	16.24	0.303
Number of stops in arm	13.85	11.28	0.656	6.904	7.66	0.929	8.96	5.51	0.302
Cumulative turn when stopped in arm	1279	1106	0.860	722.14	678.53	0.632	648.68	634.81	0.939

intentional instructions spent more time stopped in the hall (average = 15.45 and 23.36), compared to the incidental group (average = 4.25 and 14.92). In the closed arm trial, subjects who received incidental instructions cover a significantly longer distance in the hall (average = 35.19) compared to the intentional group with an average of 15.84. These results indicate that, in contrast to the familiarization and learning phases, that the intentional group traversed more in the central hall, in the test phase the incidental group cover more distance than the intentional group. Furthermore, the average number of stops in the hall and cumulative turn when the subjects are stopped in the hall for the intentional group, in star retrieval trial, are 7.38 and 594.76, respectively, which are significantly higher, compared to the incidental group with the average of 3.80 and 222.23. A difference was also found in the time stopped in the arm for the intentional group with an average of 12.20 compared to the incidental group, with an average of 6.17 in star retrieval trial.

Additionally, significant differences were found for arms exploration in terms of the times the subjects move back and forth to targets in both star retrieval and closed arm trials. Surprisingly, the time spent for moving to the target and back from the target in incidental group is significantly higher than the intentional group in contrast to the familiarization and learning phases.

Nevertheless, there is no significant difference between two groups in the third trial of the test phase (open-arms trial), but the subjects' walking time in the hall and distance in the hall are very close to being significant between intentional and incidental groups ($p = 0.051$ and $p = 0.051$ respectively). In the open-arms trial, the incidental group tends to spend more time for walking in the hall with an average of 4.53 than the intentional group with an average of 2.41 and also the traversed distance by the incidental group with an average of 26.25 is much higher than the intentional group with an average of 13.91.

Effect of intentional and incidental learning on exploration strategies

To analyze more in-depth the effects of the given instructions on the navigational preferences, we divided the central hall into two virtual areas. An inner hexagonal region (internal region), an outer 'ring' (external region) obtained by subtracting the internal region from the overall hall area. We then computed the ratio between the distance covered in the external region and in the internal one for each subject. The same ratio was calculated for the time spent as well (Fig. 2).

In the familiarization phase, both intentional and incidental group presented a ratio > 1 for distance covered and time spent, meaning that both groups preferred to navigate the

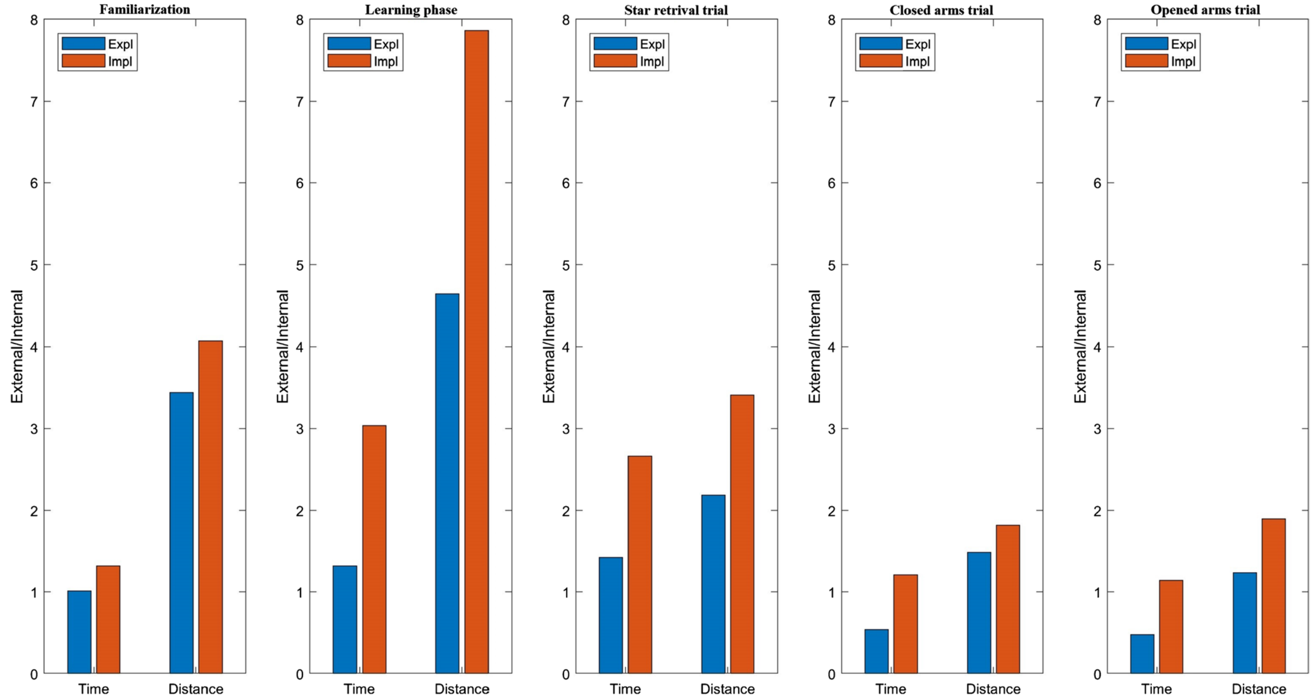

Fig. 2 The effects of the incidental and intentional instructions on the navigational preferences. The ratio of time and distance in the external region to the internal for each group

external region longer. Statistical comparisons between the ratios from the two groups were not significant.

In the learning phase, again, distance, and time ratios were > 1 for both groups. Comparisons showed that the incidental group presented a statistically higher ratio both for distance and time compared to the intentional group. This means that incidental instructions increased the preference of subjects to navigate the external part of the central hall, exploring less the central region.

The same results were obtained for the first trial of the test session (star retrieval). The second and third trials of the test phase (closed-arms and open-arms trials) showed a similar picture, but in both cases, the ratio for the time was < 1 for the intentional group. The statistical tests showed again a significantly higher preference for the external region in the incidental group. These results imply that in session closed arms and opened arms trials, subjects presented with intentional instructions spent more time navigating the internal region of the hall compared with the external one, while subjects from incidental groups still preferred the external region over the internal one. In Fig. 3, for better clarity, we illustrated the navigational routes of three subjects from each group who received incidental and intentional instruction.

Furthermore, during the Debriefing phase, our subjects were provided with a few more questions about their experience in the virtual maze and we collected their impressions in a qualitative fashion. We did not have a structured questionnaire to collect all the answers, but participants from the Incidental learning group openly reported that they did not adopt a well-planned navigational strategy at first; furthermore, most of them did not expect memory evaluations afterwards. Some of these participants even declared that the task was quite difficult for them, since they did not expect they should have memorized the environment.

Discussion

In this study, to assess the individual differences in human spatial navigation, we presented an art gallery-like virtual radial arm maze. Our initial assessment revealed that the different set of instructions could affect the participants' navigational performance during both learning and recall phases, and generally, the participants who received the intentional instruction showed better performance than the other group. Moreover, based on the received instruction, these two groups adopted a different navigational strategy in the main hall of the art gallery.

Previous studies on human navigation (Auger et al. 2012, 2017; Cornwell et al. 2008; Etchamendy and Bohbot 2007; Hartley et al. 2003) have not investigated in detail which behavioral variables distinguish both 'intentional' and 'incidental' navigators in the context of spatial mazes, and thus which spontaneous exploration strategies are adopted according to the task demands. Even though our study is merely exploratory, we believe the novelty of our study resides in our experimental paradigm: we collected a series of behavioral measures and the analysis of path lengths of our participants to extract exploration and navigational strategies, and we created two questionnaires (Environmental knowledge and Artwork recognition questionnaires) and a blank map of our maze to distinguish our subjects based on their performance, by considering, in addition, their working and reference memory errors in all trials of the test phase.

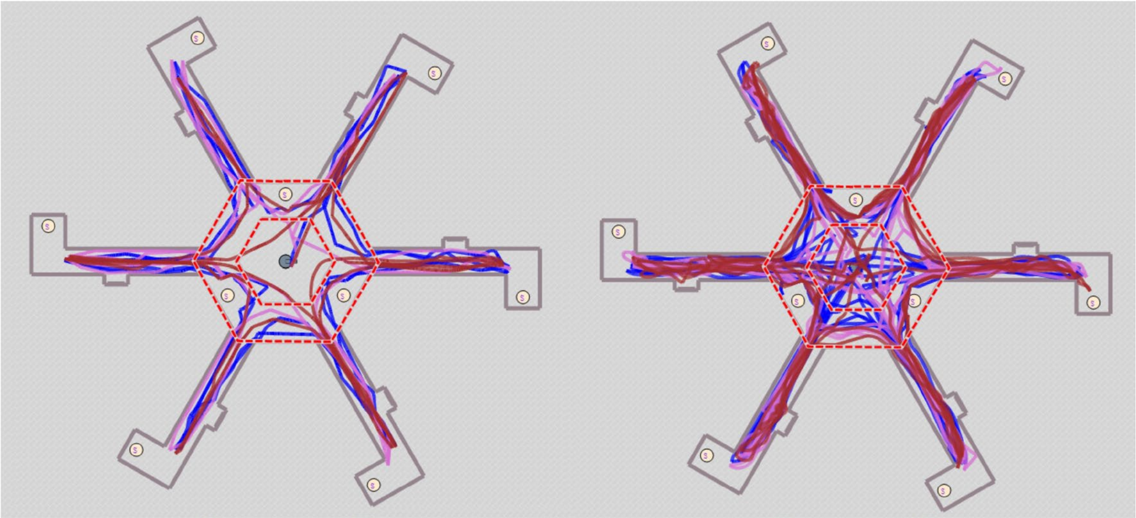

Fig. 3 (Left). The navigational routes of three subjects from the incidental group (Right). The navigational routes of three subjects from the intentional group

Another aspect that distinguishes our study from previous ones (e.g., (Ferguson and Hegarty 1994)) is our control over the type of directives provided to participants from the first experimental phases and the assessment of approaches derived from these instructions, that were either intentionally informative or not. The results show that subjects who receive intentional instructions about the task demands generally perform better than participants who only have access to incidental instructions.

The questionnaire and map test show the participants who received the intentional instruction are significantly better in the correct matching between each central statue and the two paintings in the two respective adjacent arms, independently from the statues in the same arms. Moreover, the participants in the intentional group are significantly better in arm pairing, which means their performance in the correct matching of each painting-statue pair, independently from the arm in which they are positioned, was better than the incidental group. The errors analyzed during the test phase show that the subjects who received the incidental instruction made more working and reference memory errors in the first and second trials of the test phase. This finding evidently shows that the group who wasn't forced to pay attention to all contextual features of the environment and to remember the positions of all artworks exposed in the art gallery during the familiarization and learning phases couldn't learn the maze environment well and showed a weaker performance at the testing phase. The most interesting results were achieved in the deep and detailed analysis of the subject's behavior in all phases of the experiment. We segmented the whole maze to two main regions, which are central hall and arms, then the subject's behavior within these parts was analyzed separately.

Due to the content of the intentional set of instructions, the obvious reaction would be to spend enough time to memorize all details and to look around, searching for a concrete strategy in navigation. The current results evidently show that the intentional group spent more time in the familiarization and learning phase, and they are much slower than the incidental group because of the given instruction. The outcome is that the intentional group spent more time in the environment and stopped in the main hall, they covered a longer distance in the maze (and thus being slower), they stopped a lot to see all details, and they looked around while walking during both familiarization learning phases. The other group, on the other hand, performed only a superficial exploration of the maze in the first two phases, spending less time in the environment and traveling less. Even though the two sets of instructions were meant to influence the navigational performance of our subjects, it should be reported that we do not exclude that some of our participants adopted some memory strategy even when not given intentional instructions. This aspect might be considered a limit of the present investigation; therefore, we do not exclude that individual strategies may have had a role in our participants' performance. Future studies are needed to exclude this assumption.

Nonetheless, we could not find significant differences for the total time in the test phases, but the results clearly show that the intentional group was surprisingly faster than the incidental group in the test trials. The spontaneous strategies changed during the test trials, with participants from the intentional learning group traveling less, but spending more time in the main hall than the other group. It seemed that intentional learners based their orientation strategy on the features of the main environment by spending a lot of time still in the same place, which is contained the central statues that were usually considered as reference landmarks for navigation. The amount of time spent still in the hall during familiarization emerged to be a good performance prediction factor: in general, participants who stopped more in the main hall performed better in the map completion and made fewer errors than the other participants. Actually, stopping in the main hall enables participants to look around and concentrate on which steps should be played out afterward. On the other hand, participants who performed incidental learning traveled more in the environment during the test trials, and they spent more time in the maze. It seemed that those subjects had to compensate afterward, during those last trials, the lack of attention paid toward details during familiarization and learning phases.

As already mentioned, the intentional group spent more time in the familiarization and learning phases, so consequently, they performed the task faster in the test trials. Regarding this conclusion, there are two very interesting features which are the time the subjects spend to move to the target and back from the target toward the main hall. Although there is no significant difference between the intentional and incidental group when they move back and forth from the target in the familiarization and learning phase, but the subjects who received the intentional instruction spent significantly less time to move back and forth from the targets in the test phase, and they perform much faster than the incidental group. This finding shows that, during navigation, subjects in the intentional group made their decision based on the available spatial information of the main hall while, on the other hand, the incidental group tended to move straight-forward to the targets without changing direction or being in doubt during move toward the arms.

In this study, we also directly addressed the effect of given instructions (intentional and incidental) on the subject's exploration strategies. To do so, we divided the central hall into two areas, which were named internal and external regions. We observed that the subjects who received the intentional instructions surprisingly spent more time and also explored more the internal area of the central hall, whereas the incidental group tended to navigate in the external part of the central hall.

Our study is not without limitations. First of all, as reported previously, our subjects might have adopted personal memory strategies during exploration and navigation, regardless of their experimental group and their given sets of instructions. Secondly, since our study was merely exploratory, no previous studies have reported the behavioral and test scores that we collected in our participants' experimental sessions: the consequence is that we collected a very huge number of test scores and we did not combine them into complex scores. We plan to replicate our findings in future studies, and verify whether it would be possible to combine several performance test scores into general indexes. A third aspect that should be considered is that it might be possible that the time spent in the environment, and not the instruction, is the reason for the better performance in the recall task of our subjects. Since our experiment had an exploratory nature, we decided to give our subjects an unlimited amount of time, also because we did not know what amount of time would be sufficient and appropriate for our subjects. Furthermore, the unlimited time for navigation enabled us to find out whether the type of instructions would lead to a different amount of time spent in the maze. However, future studies with a prefixed amount of time for exploration and navigation would help us understand whether it is the time spent in the environment or the instructions the crucial element for the better performance of the participants in the intentional instruction group.

Conclusion

We believe that the current results provide further evidence about the existence of behavioral differences in spatial navigation among two groups of individuals. This individual variability results in distinct spontaneous strategies to achieve the situation demands, and these strategies can vary according to the type of instruction (intentional and incidental). Relatively to our tasks, the most successful strategy resulted in being characterized by accurate navigation during familiarization, with subjects spending more time in the environment, traveling a lot to memorize all features, and turning around to notice all details. Specifically, it emerged that the time that subjects spent stopped in the main hall of the environment, where the central landmarks are positioned, was indicative of the quality of their following performance.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10339-021-01022-9.

Declarations

Conflict of interest H.T Gorji, M Leocadi, F Grassi, and G Galati state that there are no conflicts of interest.

Ethical approval All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975 (in its most recently amended version). Informed consent was obtained from all participants included in the study.

References

Astur RS, Tropp J, Sava S, Constable RT, Markus EJ (2004) Sex differences and correlations in a virtual Morris water task, a virtual radial arm maze, and mental rotation. Behav Brain Res 151(1–2):103–115

Auger SD, Mullally SL, Maguire EA (2012) Retrosplenial cortex codes for permanent landmarks. PloS One 7(8):e43620

Auger SD, Zeidman P, Maguire EA (2017) Efficacy of navigation may be influenced by retrosplenial cortex-mediated learning of landmark stability. Neuropsychologia 104:102–112

Ayaz H, Allen SL, Platek SM, Onaral B (2008) Maze Suite 1.0: A complete set of tools to prepare, present, and analyze navigational and spatial cognitive neuroscience experiments. Behav Res Methods 40(1):353–359

Ayaz H, Shewokis PA, Curtin A, Izzetoglu M, Izzetoglu K, Onaral B (2011) Using MazeSuite and functional near infrared spectroscopy to study learning in spatial navigation. J Visual Experim JoVE (56)

Bischof WF, Boulanger P (2003) Spatial navigation in virtual reality environments: an EEG analysis. Cyberpsychol Behav 6(5):487–495

Bohbot VD, Copara MS, Gotman J, Ekstrom AD (2017) Low-frequency theta oscillations in the human hippocampus during real-world and virtual navigation. Nat Commun 8:14415

Cornwell BR, Johnson LL, Holroyd T, Carver FW, Grillon C (2008) Human hippocampal and parahippocampal theta during goal-directed spatial navigation predicts performance on a virtual Morris water maze. J Neurosci 28(23):5983–5990

Dabbs JM Jr, Chang E-L, Strong RA, Milun R (1998) Spatial ability, navigation strategy, and geographic knowledge among men and women. Evol Hum Behav 19(2):89–98

DeKeyser R (2008) 11 incidental and intentional learning. The handbook of second language acquisition 27:313

Dubreuil D, Tixier C, Dutrieux G, Edeline J-M (2003) Does the radial arm maze necessarily test spatial memory? Neurobiol Learn Mem 79(1):109–117

Etchamendy N, Bohbot VD (2007) Spontaneous navigational strategies and performance in the virtual town. Hippocampus 17(8):595–599

Ferguson EL, Hegarty M (1994) Properties of cognitive maps constructed from texts. Mem Cognit 22(4):455–473

Goodrich-Hunsaker NJ, Hopkins RO (2010) Spatial memory deficits in a virtual radial arm maze in amnesic participants with hippocampal damage. Behav Neurosci 124(3):405

Hartley T, Maguire EA, Spiers HJ, Burgess N (2003) The well-worn route and the path less traveled: distinct neural bases of route following and wayfinding in humans. Neuron 37(5):877–888

Hegarty M, Richardson AE, Montello DR, Lovelace K, Subbiah I (2002) Development of a self-report measure of environmental spatial ability. Intelligence 30(5):425–447

Hodges H (1996) Maze procedures: the radial-arm and water maze compared. Cogn Brain Res 3(3–4):167–181

Iaria G, Petrides M, Dagher A, Pike B, Bohbot VD (2003) Cognitive strategies dependent on the hippocampus and caudate nucleus in human navigation: variability and change with practice. J Neurosci 23(13):5945–5952

Jacobs WJ, Thomas KG, Laurance HE, Nadel L (1998) Place learning in virtual space: II. Topographical relations as one dimension of stimulus control. Learn Motiv 29(3):288–308

Kassa J, Bajgar J, Kuca K, Jun D (2015) Behavioral Toxicity of Nerve Agents *Handbook of Toxicology of Chemical Warfare Agents* (pp. 477–487): Elsevier

Kearns R, Moon G (2002) From medical to health geography: novelty, place and theory after a decade of change. Prog Hum Geogr 26.5:605–625

Kelly DM, Gibson BM (2007) Spatial navigation: Spatial learning in real and virtual environments. Compar Cogn Behav Rev 2

Kim H, Park JY, Kim KK (2018) Spatial learning and memory using a radial arm maze with a head-mounted display. Psychiatry investigation 15(10):935

Konishi K, Bohbot VD (2013) Spatial navigational strategies correlate with gray matter in the hippocampus of healthy older adults tested in a virtual maze. Front Aging Neurosci 5:1

Konishi K, Bhat V, Banner H, Poirier J, Joober R, Bohbot VD (2016) APOE2 is associated with spatial navigational strategies and increased gray matter in the hippocampus. Front Hum Neurosci 10:349

Levy LJ, Astur RS, Frick KM (2005) Men and women differ in object memory but not performance of a virtual radial maze. Behav Neurosci 119(4):853

McNamara TP (1986) Mental representations of spatial relations. Cogn Psychol 18(1):87–121

Newcombe NS (2018) Individual variation in human navigation. Curr Biol 28(17):R1004–R1008

Olton DS, Samuelson RJ (1976) Remembrance of places passed: spatial memory in rats. J Exp Psychol Anim Behav Process 2(2):97

Ruddle RA, Payne SJ, Jones DM (1997) Navigating buildings in" desktop" virtual environments: Experimental investigations using extended navigational experience. J Exp Psychol Appl 3(2):143

Spriggs MJ, Kirk IJ, Skelton RW (2018) Hex Maze: A new virtual maze able to track acquisition and usage of three navigation strategies. Behav Brain Res 339:195–206

Stadler MA (1997) Distinguishing incidental and intentional learning. Psychon Bull Rev 4(1):56–62

Tarragon E, Lopez L, Ros-Bernal F, Yuste J, Ortiz-Cullera V, Martin E, Richardson J (2012) The Radial Arm Maze (RAM) for the evaluation of working and reference memory deficits in the diurnal rodent Octodon degus. Paper presented at the Proceedings of Measuring Behavior

Thornton A, Lukas D (2012) Individual variation in cognitive performance: developmental and evolutionary perspectives. Philos Trans Royal Soc London B 367(1603):2773–2783

Tolman EC (1948) Cognitive maps in rats and men. Psychol Rev 55(4):189

Tolman EC, Honzik CH (1930) Introduction and removal of reward, and maze performance in rats. University of California Publications in Psycholog

Ugwitz P, Juřík V, Herman L, Stachoň Z, Kubíček P, Šašinka Č (2019) Spatial analysis of navigation in virtual geographic environments. Appl Sci 9(9):1873

van Asselen M, Fritschy E, Postma A (2006) The influence of intentional and incidental learning on acquiring spatial knowledge during navigation. Psychol Res 70(2):151–156

Walkowiak S, Foulsham T, Eardley AF (2015) Individual differences and personality correlates of navigational performance in the virtual route learning task. Comput Hum Behav 45:402–410

Williams B, Myerson J, Hale S (2008) Individual differences, intelligence, and behavior analysis. J Exp Anal Behav 90(2):219–231

Wolbers T, Hegarty M (2010) What determines our navigational abilities? Trends Cogn Sci 14(3):138–146

Wood RA, Bauza M, Krupic J, Burton S, Delekate A, Chan D, o'Keefe, J. (2018) The honeycomb maze provides a novel test to study hippocampal-dependent spatial navigation. Nature 554(7690):102