Faculty of Medicine and Psychology

BRAIN DYNAMIC DURING LANDMARK-BASED LEARNING SPATIAL NAVIGATION

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Abstract

In the current study, I investigated both human behavior and brain dynamics during spatial navigation to gain a better understanding of human navigational strategies and brain signals that underlie spatial cognition. To this end, a custom-built virtual reality task and a 64-channel scalp electroencephalogram (EEG) were utilized to study participants.

At the first step, we presented a novel, straightforward, yet powerful tool to evaluate individual differences during navigation, comprising of a virtual radial-arm maze inspired to the animal experiments. The virtual maze is designed and furnished, similar to an art gallery, to provide a more realistic and exciting environment for subjects' exploration. We investigated whether a different set of instructions (explicit or implicit) affects subjects' navigational performance, and we assessed the effect of the set of instructions on exploration strategies during both place learning and recall. We tested 42 subjects and evaluated their way-finding ability. Individual differences were assessed through the analysis of the navigational paths, which permitted the isolation and definition of a few strategies adopted by both subjects who adopted a more explicit strategy, based on explicit instructions, and an implicit strategy, based on implicit instructions.

The second step aimed to explore brain dynamics and neurophysiological activity during spatial navigation. More specifically, we aimed to figure out how navigational related brain regions are connected and how their interactions and electrical activity vary according to different navigational tasks and environment. This experiment was divided into two steps: learning phase and test phase. The same virtual maze (art gallery) as the behavioral part of the study was used so that subjects to perform landmark-based

navigation. The main task of the experiment was finding and memorizing the position of some goals within the environment during the learning phase and retrieving the spatial information of the goals during the test phase. We recorded EEG signals of 20 subjects during the experiment, and both scalp-level and source-level analysis approaches were employed to figure out how the brain represents the spatial location of landmarks and targets and, more precisely, how different brain regions contribute to spatial orientation and landmark-based learning during navigation.

List of Contents

List of Figures

List of Tables

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General Introduction

1.1. Abstract

Individual navigational skills were then used daily in navigating locations within the small or large environs, such as homes or cities. Navigation to goal destination within such environs enables individuals to attain various tasks in a more productive manner such as banking, shopping, committing to work, etc. The following study will bring to the discussion other concepts such as identifying the human brain structure that supports such complex navigational skills, the forms of information that are essential during spatial navigation process, numerous theories, and many years of research have also contributed to human understanding of the already existing theories.

One of the first studies on the human spatial learning process can be traced back to 1913 at a time when (TroWBriDgE, 1913) has investigated the use of the various "imaginary maps" by humans in an oriented task. Later in 1948, (Edward C Tolman, 1948) coined the term "cognitive map" to explain the internal mental presentation of the physical space that both humans and animals implement in finding their way, uniquely when identifying novel shortcuts, and when navigating in actual-world situations. Ever since, the term has always been used at large in literature alongside having inspired various groups in exploring the concept behind the term and he methodological challenge. The cognitive map's existence, including other forms of spatial data acquired during navigation, has all become a hot topic of debate over decades. (Siegel & White, 1975) brought to the proposal that humans are capable of acquiring the route knowledge depending on the landmark sequences, including other distinct local cues, and the survey knowledge of a spatial layout depending on the environmental properties.

An excellent example of route knowledge acquisition is merely driving or walking along the streets while exposed to the local view surroundings, and other prominent landmarks. Survey knowledge can be obtained either through an aerial view of a map or merely looking at the map of a town containing highways, streets, rivers, or other general

locations such as the historical monuments. The expressive support for the cognitive maps did emerge from the earlier cellular rodent studies whereby the rodents were expected to navigate a maze and to attain specific landmarks alongside choosing the new paths between locations found to be familiar (O'Keefe & Conway, 1978; O'Keefe & Dostrovsky, 1971; O'keefe & Nadel, 1978). Over the last few decades, essential progress in studying the animal navigational processes had been provided a foundational comprehension for the transition into research on the human spatial memory.

Inferring to humans, the last few years have exposed remarkable progress in spatial memory research because the interest in human studies has been increased unprecedentedly, favorable technology development, and experimental practices that are safer and that which involve human subjects. There has been a plethora of electrophysiological, neuroimaging, and behavioral studies attempting to explain the neural, cognitive, and anatomical base for how human beings navigate through the environment. Numerous studies employ either a computer-generated or real-world setting. With innovations technologies and methodologies, recent studies proceed into exploring the structural and functional brain networks to spatial navigation. Many such types of research converge on the interests to comprehending how humans encode, update, manipulate, and retrieve the environmental-related spatial information. In the following, a review is provided over the relevant current literature that addresses this topic.

1.2. Behavioral studies of spatial navigation

The behavioral studies do enable one to follow navigational behaviors in either the virtual or real environment. Both the strategies and acquisition of the spatial information can be taken to study through manipulating the visuospatial properties and constraints of the different environs. Additionally, the study will also explore the content, information, and the retrieval of a mental presentation of space. Lastly, the study shall uncover the underlying human spatial cognition.

The recent years because of the significant progress in computer simulation, many spatial navigation studies are implemented in the virtual environment. However, still, there exist a few behavioral studies that employ a real-world environment. (Israel, Grasso, Georges-Francois, Tsuzuku, & Berthoz, 1997) came up with a more advanced manner of studying the memory for linear distance through implementing passive transport. In such type of navigation, the blindfolded participants utilized a joystick-controlled robot in movement alongside the linear trajectories. The individuals were asked to reproduce the distance they already experience in the dark, and the subjects were accurately able to reproduce the stimuli distances, peak velocities, durations, and velocity profiles. The accurate distance estimations were attributed to the integration of the Otolith signals. The paradigm results illustrated the vestibular and the somatosensory cues did issue during passive transport assistance in the molding of a dynamic and static travel path representation.

Additionally, the study also emphasized the necessity of memory for a linear displacement in the path integration process, with a continuous update of an individual's or animals' position concerning the other subjects in the environment, and alongside other abilities such as finding shortcuts. Hence, in this study, the non-visual information to human spatial memory that usually neglected during routine navigational experiences was studied. A study was implemented by (Wang & Spelke, 2000) to explore how object location in the environment could be represented. In the learning phase, subjects studied object locations positioned outside the test chamber. After fruitful learning of the objects being confirmed, the subjects were then asked to provide specifications as to where the unseen objects could be from the inside of the chambers. This had been conducted for conditions in which the subjects were either oriented or disoriented by self-rotation. The heading and configuration of responses, which respectively represent the absolute and relative accuracy, were measured. Disorientation did increase both the configurational and heading errors while at the same time, the existence of light cue through the entire study did produce the opposite effect. The study settled to the conclusion that the object locations, including direction and distance, had all been egocentrically represented in the mental representation of space, which continuously updated by humans during movement. An extension of such findings was then formulated by (Burgess, Spiers, & Paleologou, 2004) in a study where the researchers investigated the influence of external landmarks on a spatial updating ability. In their study, the subjects' task was to assess any variation in the position of the objects within an array on a table after having spent a period in the dark. During such a stage in darkness, the table, objects, the subjects, and/or an externally placed a fluorescent card could have been moved. The study results then suggested that besides an egocentric representation, the object's locations had been represented concerning the visual landmarks that had been positioned outside the array of interest, such as through an allocentric representation.

Although the spatial navigation experiments that are implemented in real-world environments could lead to more realistic and reliable results, there are some limitations regarding stimuli manipulation, visual properties, and task flexibility. Further, because of the significant progress in understanding the human spatial navigation mechanism, the need for more sophisticated experiments and tasks is felt more and ever. Advancements in computer technology can open a new door to overcome such limitations.

With the current advancements in graphics and computer hardware, researchers are capable of creating virtual environments for research, construction, and training purposes. Such virtual environs can be implemented to model a real environment or even create such environments that are not easily accessible to humans. In such a manner, such improved technology will create a safe, flexible, and convenient alternatives in conducting human spatial navigation research. Moreover, data acquisition and navigational behaviors can be recorded and measured automatically and more precisely. In most cases, subjects explore virtual environments using a standard control device such as a keyboard, mouse, or a joystick. It is worth mentioning that the virtual environment is never perfect as it comprises of its own set of challenges and limitations. One of the main concerns which can be raised from virtual environment-based studies is to what extend navigational learning in such environments could be similar to the real-world environments. (Witmer, Bailey, Knerr, & Parsons, 1996) assessed the effectiveness of learning from a virtual environmental model of a complex office structure to navigate in an actual building. The study results demonstrated that the virtual environments with sufficient complexity had been the most effective as the actual world environment for learning specific routes. The subjects were capable of transferring the route knowledge relatively from the virtual environment model to the actual building. Due to the lack of enough exposure to the virtual environment, they could not test whether survey-knowledge can be acquired in a virtual environment or not.

(Ruddle, Payne, & Jones, 1997) came by a study whereby, after a substantial practice in a larger scale virtual structures, subjects were significantly more oriented. Additionally, the results of a map-construction task if the virtual environment showed that the subjects were capable of learning the new routes efficiently alongside developing a relatively accurate survey knowledge. Hence, due to the comparable spatial knowledge obtained from both the virtual and real environment (Richardson, Montello, & Hegarty, 1999; Ruddle et al., 1997; Waller, Hunt, & Knapp, 1998; Witmer et al., 1996), a similar spatial environ mechanisms, and a mental presentation of space could be included.

Another potential limitation of spatial navigation experiments in the virtual environment is the absence of vestibular and proprioceptive cues. According to a study by (Klatzky, Loomis, Beall, Chance, & Golledge, 1998), the simulated optic flow, as opposed to physical walking, had been less effective for updating heading given the more heading errors. Hence the vestibular and the proprioceptive input enhance spatial learning, and likely this gave an explanation as to why the subjects experienced challenges staying oriented in a virtual environment once exposed for a short period (Richardson et al., 1999). However, the subjects were able to learn and efficiently navigate through virtual environments.

(Kirschen, Kahana, Sekuler, & Burack, 2000), investigated the influence of landmarks and optic flow on learning of T-junction mazes. The results of their experiment indicated that with the existence of optic flow, the subjects were capable of learning the mazes much faster by being less disoriented compared to the absence of optic flow, especially whenever a visual landmark does not exist. The landmarks and optic flow enabled the subjects to reorient themselves and learn the sequences of turns in the maze, by lower inter-response times for making turns. It is obvious the optic flow and landmarks play an essential role in learning the spatial information alongside constructing a mental representation during spatial navigation.

1.3. Electrophysiological studies on spatial navigation

Electrophysiological research, like the scalp and intracranial electroencephalography tests and single-unit recordings, enables the monitoring and a better understanding of human brain function during spatial navigation activities. Different sizes of electrodes can be utilized based on the approach and purpose.

Intracranial electroencephalography (iEEG) refers to an invasive, electrophysiological approach designed to accurately monitor and record electrical activity from a number of neurons (i.e., typically several thousand) in different cortical areas. The iEEG has remarkably higher temporal resolution compared to the neuroimaging approaches such as functional magnetic resonance imaging (fMRI) and positron emission tomography (PET). Also, iEEG provides much better spatial resolution compared to scalp EEG, without muscle artifact and brain signal reduction because of the scalp and skull. There exist comparatively few research groups using iEEG, while the majority of studies being carried out in the clinical environment. A practical concern of iEEG is that the regions could be selected that are appropriate for neurosurgical procedures. Hence, there is a limitation in recording and analyzing the signals from the region of our interest. However, iEEG may effectively be utilized to study mechanisms of spatial navigation in humans with a neural disorder, such as patients with brain tumors and epilepsy.

(Kahana, Sekuler, Caplan, Kirschen, & Madsen, 1999) recorded iEEG from 3 epileptic patients who were injected using subdural electrode arrays on the surface of ventral cortical to localize seizure foci locations. In the meantime, subjects tried to traverse virtual T-junction mazes quickly and accurately, comprising of several corridors, from beginning to goal locations. Some participants discovered short (6-turn) and long (12-turn) corridors by tracking arrows (learning phase) and had to traverse the exact same maze by only employing their own knowledge (test phase).

Control of movement was somewhat restricted in a case where a single keypress created a complete corridor traversal or a 90-degree turnaround. In both the learning and the test phases, the data showed distinct, non-continuous, and task-dependent periods of rhythmic theta wave (4-8 Hz) activity in different cortical areas, including the temporal cortex. Time-frequency analysis and average power spectra showed that the likelihood of having a theta episode seemed to be considerably higher during navigation of longer maze than the shorter one. Furthermore, 45 electrodes indicated that theta waves are more likely to happen during the test phase (i.e., retrieval of memory) than during the learning phase (i.e., encoding). Therefore, it seems theta wave activities more associated with maze complexity and memory retrieval. Further research endorse and expand the results set out above.

(Caplan, Madsen, Raghavachari, & Kahana, 2001) also analyzed iEEG activity of 5 epileptic patients who traversed the virtual T-junction maze. They utilized a new oscillatory detection algorithm to exploits the rhythmic activity in 2 to 45 Hz from high spatial and temporal resolution of iEEG. The relationship between the probability of having an activity episode at a specific frequency (P-episode) and the length of the maze and decision time at maze intersections were analyzed. Results showed that oscillatory activity majorly took place in the theta band. The P-episode for theta wave was increased in several brain regions with the length of the maze while it did not significantly change with decision time, which is linked to cognitive processing. The impact of the length of the maze was discovered within the alpha band, as well. P-episode for delta and gamma was identified to co-vary with decision time. Generally, this study's results expand previous findings of brain activity during virtual spatial navigation. It seems theta activity appears to correspond to task requirements, such as maze difficulty level, while delta and gamma waves are linked to memory processes like encoding and retrieval.

In another study by (Caplan et al., 2003), they investigated the relationship between theta wave and spatial learning and sensorimotor integration during navigation in a virtual city. To do so, iEEG of twelve epileptic patients was recorded during foraging (searching and picking up passengers from different places) vs. goal-seeking (transport them to desired locations) and standing still vs. moving. The results showed more theta wave activity during movement than the subjects were still in the virtual city. Further, the theta wave was more frequent during foraging in the temporal lobe and peri-Rolandic region while during goal-seeking, theta wave was observed during movement more in the right hemisphere and less in dorsal regions. Moreover, strong beta activity was observed during movement in the pre-Rolandic region, and less gamma activity was modulated by movement vs. non-movement. In conclusion, the researchers suggested that gamma wave is more related to sensory and memory-related activity during foraging, theta oscillation is responsible for coordinating and interacting with different brain regions, and the beta wave is more involved in motor-planning during goal seeking.

In contrast to iEEG, scalp EEG is a non-invasive technique that records brain signals from the scalp. Due to the nature of EEG, the presence of muscle artifacts is inevitable, and the raw EEG signal must be cleaned before the main analysis. The adjustment of EEG electrodes is more flexible that iEEG, and there is no need for a clinical setting; however, the temporal and spatial resolution of EEG is lower than iEEG. In comparison with fMRI and PET, the EEG has a lower spatial resolution and much higher temporal resolution. However, it seems because of its lower spatial resolution, the EEG is not much widespread as imaging techniques such as fMRI in human spatial navigation experiments. Nevertheless, there are some research groups studied or doing their research based on this approach for analyzing spatial navigation.

(Nishiyama & Yamaguchi, 2001) utilized a 64-channel scalp EEG to record the brain activity of 3 participants while traversed to a target in two versions of the short and long virtual maze. Theta wave elicited by using band-pass filtering (5-8 Hz) and Fast Fourier transformation (FFT), and then the data was projected into a 2D map. This experiment revealed the same result as (Caplan et al., 2001; Kahana et al., 1999), which showed the length of the maze modulated the theta oscillations. Based on the 2D map, the theta bursts were sequentially (not with a fixed order) observed in frontal and temporoparietal regions. The authors stated that “complex dynamics of informational flow” is the reason for variety in sequential activation, and it indicates the functional connectivity among the prefrontal cortex, parietal cortex, and hippocampus, which may be associated with human spatial cognition.

(Bischof & Boulanger, 2003) utilized T-junction maze identical to (Kahana et al., 1999) experiment, but to make the movement more natural, the control overturning was increased the viewpoints were changed more realistic. The EEG of fourteen subjects was recorded when they were navigating through two non-colored and colored mazes. For each maze, time points and positions of every theta episode are determined, and spectrograms and Fourier transforms were calculated. The colored maze was more complex than the non-colored maze, and participants explored the colored maze last longer with making more errors because of the use of a much more time-consuming and complex learning strategy. The EEG analyzing results showed that there is a correlation between maze complexity and theta activity because the power of the theta waves seemed to be higher for the colored maze. Additionally, theta episodes happened more often with a higher power either instantly after a turn where new hallway come into view, or after navigational mistakes have been realized and are being corrected. The findings of this study revealed that there is a direct relationship between theta waves and coding and retrieval of spatial knowledge during navigations.

In the following study, (White, Congedo, Ciorciari, & Silberstein, 2012) investigated brain oscillatory correlated of spatial navigation utilizing blind source separation (BSS) and standardized low-resolution electromagnetic tomography (sLORETA) analyses of 62-channel EEG recordings. They employed twenty-five participants to learn a virtual reality town environment and then instructed to navigate to some distinct landmark buildings. The BSS approach was used to obtain source components from the EEG data in the period of navigation between landmarks. Two of the significant sources were localized as the right parietal component with gamma activation and a right medial-temporal–parietal component with activation in theta and gamma bands. They reached the conclusion that the parietal gamma activity was thought to reflect visuospatial processing associated with the task, and the medial-temporal–parietal activity was more specific to the navigational processing, representing the integration of egocentric and allocentric representations of space required for successful navigation. They suggested that theta and gamma oscillations may have a role in integrating information from parietal and medial-temporal regions, and theta activity on medial-temporal–parietal source was positively correlated with more efficient navigation performance.

Although the above-mentioned EEG studies revealed that some brain regions such as the hippocampus, frontal, prefrontal, parietal cortex, peri-Rolandic region, etc. alongside gamma, theta, and beta bands are involved in human spatial navigation, still further researches with more complex tasks are needed. (Lin, Chiu, & Gramann, 2015) investigated the brain dynamics in the regions were involved in spatial navigation, specifically Retrosplenial complex (RSC), which plays a crucial role in processing allocentric spatial information. The authors analyzed the individual spatial reference frame (SRF) proclivities during navigation to understand its impact on navigationally related brain regions. A 64-channels EEG set up, and an analyzing method based on spectral perturbation is used to investigate the function of RSC during navigation with high temporal resolution. Twenty-one participants were asked to perform a path integration task in a virtual environment with clear allocentric information. A control condition with the same visual input, but no orientation task was used to investigate the reference frame specific orientation processes by time-frequency transformation. Based on the final results, the egocentric navigators showed significantly stronger theta power increases in the medial frontal cortex and beta increases in the motor cortex while allocentric, navigators indicated significantly stronger alpha modulation in the RSC, parietal, and occipital cortex. The authors stated that modulations in the alpha and beta band with different time courses in RSC provide the first evidence of these two distinct neural processes reflecting translation of spatial information based on distinct reference frames and computation and maintenance of heading changes, respectively.

1.4. Conclusion

Throughout this chapter, recent research on human spatial navigation were analyzed from behavioral and electrophysiological viewpoints. The aim of all studies was to add new findings or improve the existing knowledge in coding, updating, manipulating, and retrieval of spatial information. Above discussed research have indicated that virtual environment can be utilized as a powerful and effective solution for navigational studies (Klatzky et al., 1998; Richardson et al., 1999; Ruddle et al., 1997; Waller, 2000; Waller et al., 1998; Witmer et al., 1996). Behavioral findings indicated that both real-world(Burgess et al., 2004; Israel et al., 1997; Klatzky et al., 1998; Wang & Spelke, 2000) and virtual environments(Kirschen et al., 2000; Redlick, Jenkin, & Harris, 2001; Warren, Kay, Zosh, Duchon, & Sahuc, 2001) settings could be used to assess path integration strategies. Numerous research have shown that spatial knowledge can be learned through a view-based paradigm, which includes sequence memory and landmark associations(Gillner & Mallot, 1998; Grasso, Ivanenko, McIntyre, Viaud-Delmon, & Berthoz, 2000; Hamilton, Driscoll, & Sutherland, 2002; Mallot & Gillner, 2000). Certain studies appear to endorse an allocentric navigation model(Burgess et al., 2004; Hartley, Trinkler, & Burgess, 2004), consistent with the principle of "cognitive map" (Edward C Tolman, 1948).

Electrophysiological based studies have suggested cortical networks (Bischof & Boulanger, 2003; Caplan et al., 2001; Caplan et al., 2003; Kahana, Seelig, & Madsen, 2001; Kahana et al., 1999; Nishiyama & Yamaguchi, 2001; O'Keefe & Burgess, 1999) and subcortical networks (Ekstrom et al., 2003), which support spatial navigation in humans. The achieved results revealed that some brain areas such as parietal, frontal, and medial temporal regions function together to give the humans the ability of route-following, creating new routes, planning and decision making, and integration of sensorimotor information for egocentric-based and allocentric-based navigation (Bischof & Boulanger, 2003; Caplan et al., 2001; Caplan et al., 2003; Kahana et al., 1999; Lin et al., 2015; Nishiyama

& Yamaguchi, 2001; White et al., 2012). Several cortical oscillations in such as gamma, beta, and particularly in the theta band, have been involved in human spatial navigation. Numerous functions of theta oscillations have been suggested, like those that represent the complexity of navigational tasks, memory process and sensorimotor coordination (Bischof & Boulanger, 2003; Caplan et al., 2001; Caplan et al., 2003; Kahana et al., 1999). However, still, many more studies should be designed and implemented to result in a deeper understanding of brain function during spatial navigation. Scalp EEG and iEEG can be employed as effective tools to figure out how navigational related brain regions are connected and how their interactions and electrical activity vary according to different navigational tasks and environment.

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

2.1. Abstract

Human individuals differ widely in their ability to navigate effectively through the environment and in spatial memory skills. Navigation in both real and virtual environments require the analysis of many spatial cues and landmarks, the construction of many different internal representations, and the use of various spontaneous strategies.

Here we present a novel, simple, yet powerful tool to assess individual differences in human navigation, consisting of a virtual radial-arm maze inspired to the animal literature but adapted in order to provide an enjoyable experience during spontaneous exploration by human subjects. The maze is indeed presented as an art gallery, and the navigational tasks are initially concealed as a study on aesthetic judgments. In this initial assessment of this novel tool, we explore whether a different set of instructions (explicit or implicit) affects subjects' navigational performance, and we investigate the effect of the set of instructions on exploration strategies during both place learning and recall.

We tested 42 subjects and evaluated their way-finding ability. Individual differences were assessed through the analysis of the navigational paths, which permitted the isolation and definition of a few strategies adopted by both subjects who adopted a more explicit strategy, based on explicit instructions, and an implicit strategy, based on implicit instructions.

Studying how environmental representations and the relative navigational strategies vary among "explicit" and "implicit" groups provides a new window into the acknowledgment of possible strategies to help subjects to construct more efficient approaches to learn the characteristics when they find themselves in new environments.

2.2. Introduction

Individual variations in cognitive abilities are an integral part of human evolution (Thornton & 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, & Hale, 2008). Consequently, it is not unexpected that there is always inconsistency in individuals' spatial memory skills and the ability to navigate effectively through the environment (Wolbers & Hegarty, 2010). 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 & Honzik, 1930): some strategies can be adaptive to reach an end-point, whereas others can induce navigators to lose themselves upon their surroundings (Dabbs Jr, Chang, Strong, & Milun, 1998).

Mazes are essential tools in the study of spatial navigation processes. 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 et al., 1997). In recent times, the employment of virtual-reality setups has achieved increasing popularity due to more powerful and cheaper devices (Kelly & Gibson, 2007). Furthermore, literature is not void of successful attempts with full-scale mazes for real-life human navigation (Bischof & Boulanger, 2003; Bohbot, Copara, Gotman, & Ekstrom, 2017; Spriggs, Kirk, & Skelton, 2018).

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, Park, & Kim, 2018; Levy, Astur, & Frick, 2005; Walkowiak, Foulsham, & Eardley, 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). Distances, time, speed, direction changes, and favorite portions of the environment are all examples of behavioral features that characterize the 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 conventional indexes such as overall time, velocity and distance to the behavioral-based indexes of navigation, their variability among people, and how environmental and experimental conditions influence them.

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 rich 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.

There are two main types of learning which humans use in their daily life: implicit and explicit learning. Implicit learning refers to an incidental and unconscious manner for knowledge acquisition that individuals are not aware of and that they cannot even verbalize. In contrast, during explicit learning, individuals gain knowledge consciously and intentionally as they attempt to obtain such information declaratively (DeKeyser, 2008; Stadler, 1997). Explicit or implicit instructions to navigate and to learn a new environment have been proved to affect the quality of the acquired information. Explicit information tends to improve the quality of the learning process, leading to a better performance in the navigational task.

(van Asselen, Fritschy, & Postma, 2006) investigated the influence of explicit and implicit 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 explicit group performed significantly better than the implicit group on map drawing and navigational tasks. In addition, the explicit group estimated the route length to be higher than the real value, while, on the contrary, the implicit group estimated the path length to be shorter. Moreover, the two groups showed no difference when asked to recognize and order landmarks.

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 explicit instructions to learn and memorize the environment and the positions of the objects, while the other group visited the maze in order to give their opinion about the artworks presented eventually. Both groups underwent a place learning task where they learned the position of novel objects that were not present during the initial exploration. We thus verified whether the 'explicit instructions' group achieved a better performance both in terms of the number of errors and in the quality of creating the cognitive map of the environment, and we explored whether the instruction set affected exploration strategies both during the learning process and during recall.

2.3. Materials and Methods

2.3.1. The art gallery maze

Actual environments are thought of as the best means of studying and manipulating individual abilities to navigate in the environment. Nonetheless, such experiments do not permit the management of similar variables for every participant, and numerous factors such as traffic, weather conditions, and noise are all prone to affect both the performance and results. On the other hand, the virtual learning environments are referred to as an essential alternative tool used in assessing spatial navigation abilities and personal variances in humans other than being able to examine which spontaneous policies might be adopted in the numerous daily life occurrences. Additionally, they permit the regulation of those mystifying the real environments' variables.

In the following respect, we decided to set our study on a novel virtual reality environment identified as the “art gallery maze” that had been earlier created as similar as possible to an actual museum that is then furnished with artworks. A choice that is comparative to setting out tasks in an art gallery meant to make the experiment much more intriguing and absorbing for the participants. The map and creation of an experimental setting had been inspired by other studies that had adopted the radial arm maze in studying the spatial navigation skills for both the animals and humans (Etchamendy & Bohbot, 2007; Jarrard, 1986; Olton & Samuelson, 1976).

The virtual-reality environment had been initially designed to be in the shape of a radial arm maze; this had been developed with the aid of an open-source software Maze Suite (v. 3.0.1, www.mazesuite.com), developed by Hasan Ayaz and colleagues (Ayaz, Allen, Platek, & Onaral, 2008; Ayaz et al., 2011). With much ease, the maze suite facilitates the creation and visualization of a 3D environment. Nevertheless, such an environment is constituted by a whole set of tools that enables the researchers to perform spatial control, motor, and experimental navigational behaviors within an extendable and interactive 3D virtual environment. The implemented software comprised of three major applications comprising of different characteristics: Maze Walker, Maze Maker, and Maze Analyzer. The maze maker is essential since it enables the researcher to alter and create a maze environment from the inception; on the contrary, the maze walker acts as a visualization/ rendering module of the program being implemented. Lastly, the maze analyzer authorizes a performance mapping analysis.

The following study's art gallery maze will comprise of a hexagonal central room from which six arms are extended outwards symmetrically (Figure 1). Such asymmetry then maintained intending to avoid confusion or even facilitate effects when performing tasks alongside making an environment as homogeneous as possible. Such type of maze is mainly used in rodent studies; is it is an essential tool in studying both the working and reference memory inclusive of their characteristics (Olton & Samuelson, 1976). Such a maze will enable the spatial memory study, yielding an advantage that it can be easily comprehended by humans, besides the performance can also be effortlessly affected within an experimental condition. Although the radial arm maze can be engaged with more than six arms aimed at making the tasks more challenging, given that the experiment will be merely explorative, an environment will be created that entails a medium difficulty level. Every arm of the maze is then added with two lateral enlargements, one included on the left side at the mid-point in length and the other included at the end of the arm on the right side.

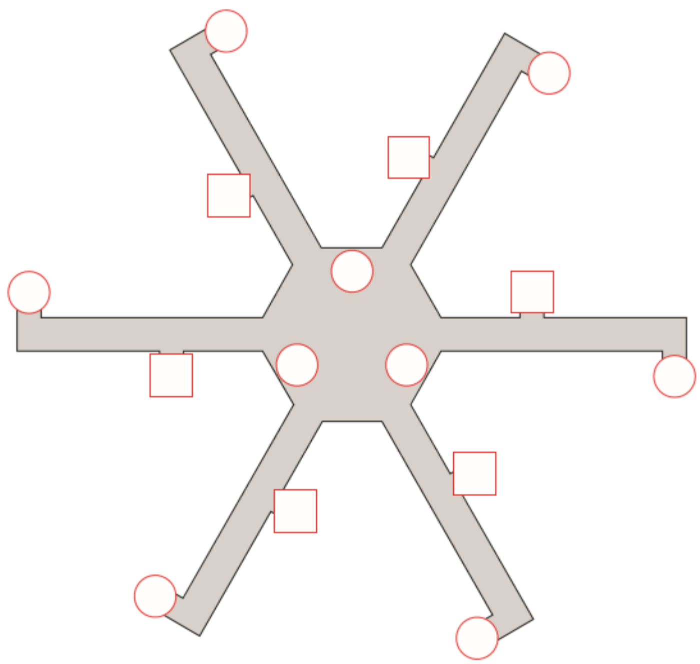


Figure 1. Maze map

The maze implemented in the following study was furnished in a manner, making it resemble a real art gallery, in the maze artworks, were exposed in all sections of the museum. Being that the museum has a central hexagonal space, we included three main landmarks along with the parameter of the maze. Each of the landmarks is then positioned in the middle between neighboring corridors. The position of the landmarks was accurately chosen in a way that every stimulus remains equidistant from the other two and the entrance of the neighboring corridors. Nevertheless, for geometrical reasons, we decided to insert three central stimuli acting as the vertices of a regular triangle. A cloudy skybox then created, and the museum left open without a ceiling to avoid a narrow and claustrophobic setting.

The measures of the maze components are listed in the following table (Table 1), with correct conversions (every 1.5 units in maze suite software corresponds to 1 meter). Since the maze suite is open-source software, we used custom MATLAB script to create the maze, that is why all the measures remained consistent along with different trials.

Table 1. Maze component measures.

Measure	Value (m)	Description
Walls heights	11.2	Museum walls heights
Square radius	29.6	Distance from the center of the main square and the entrance of each arm.
Arm's length	76.8	Length of each corridor of the maze.
Arm width	10.4	Width of each corridor of the maze.
Paintings measures	4 x 3	Width and height of each painting.
Painting distance	30	Distance from the beginning of each corridor to the center of each painting.
Enlargement width (paintings)	5.6	Width of the enlargements where the paintings were inserted.
Enlargement depth (paintings)	2.4	Depth of the enlargements where the paintings were inserted.
Enlargement width (statues)	4.8	Width of the enlargements where the statues were inserted.
Enlargement depth (statues)	8	Depth of the enlargements where the statues were inserted.
Stars distance	2	Distance between each star and the corresponding statue in the lateral enlargement.
Star height	1.4	Height of each star from the floor.
Landmarks distance	2	Distance between each landmark and the nearest wall.
Light intensity	0.3 (cd)	Environmental light intensity.

2.3.2. Landmark selection

Since the following experiment was set in a virtual art gallery, it was essential to identify some types of artworks as landmarks; we then opted for statutes and paintings. We positioned three statues in the central room of the museum, with the other six being situated in the lateral enlargements at the end of the corridors. Additionally, six paintings that had been initially meant to be hanged on the wall in the middle six lateral enlargements of the corridors.

From a larger sample of 3D objects that are freely available on the internet (in our case, from the website Archive 3D – www.archive3d.net), we selected the nine statutes with six of the statues positioned at the end of each arm and the three in the central hall. Being that the primary objectives from the website had not been similarly and uniformly colored, they did stand for the various dimensions and shades, in such a case, they were all painted white, equally sized, and made homogeneous as possible. In this respect, the goal was to make them resemble the statues exposed in an actual museum, and we used a software name Blender (www.blender.org). The blender had been initially developed by the Blender Foundation, acting as an open-source 3D computer graphics software toolset implemented in creating art, visual effects, 3D printed models, and video games.

For the paintings, the best choice depended on electing a stimulus that is as similar as possible to every item of the luminance, themes, color, and style. Hence, we selected paintings with similar characteristics, the famous and widely known paintings omitted to avoid the notion that the subjects remembered or even already knew them. We focused our choice on some paintings from the National Gallery of Art (https://www.nga.gov/), which mostly convey neutral emotional values.

2.3.2.1. Selection of paintings and statues

With the existence of choosing the artworks from a more extensive range of objects, we then settled on creating a questionnaire aimed at assessing the most suitable stimuli for the study purpose. The main aim was to identify equal objects in terms of pleasantness and salience for the study participants, and also to avoid that, the stimuli characteristics could interfere with behavioral performance. The questionnaires used comprised of surveys with two classes of stimuli (paintings and statues), from which the experimental artworks had been identified. Consisting of three sections, the first part of the questionnaire contained a welcome message with instructions and then, additionally, the preceding ones provided the different paintings and statues. From the inquiry, the artwork was rated from one to ten in terms of the likeableness index (how much do you like the item), and the salience index (to what extent this item grabs your attention). In the second section (paintings), participants were asked to rate the paintings from one to ten with 1= not at all; 10 = very much. The questionnaires were to gauge to what extent the paintings grabbed the subject's attention and how much they would prefer the picture.

The image of the painting of interest was positioned between the two questions. Twenty-two paintings, all belonging to the National Gallery of Art collection, were listed in the questionnaire. Thirty statues from Archive 3D were presented in the third section of the questionnaire, and the same kind of questions was displayed.

In the following, 84 subjects participated in the landmark selection experiment. The study subjects had been recruited through the available public social platforms such as Gmail and Facebook; besides, we ensured that the participants were not from Rome. The subject was advantaged to complete the questionnaires without any supervisory, and the answers were then later recorded in an excel sheet for future analysis. Of the 84 questions, four had been omitted from the investigation, which is that they were incomplete.

Since we used two indexes to select the paintings and statues (likeableness and salience), the mean values of both indexes for each painting were calculated among participants and are shown in the following.

As already mentioned, our museum required the insertion of six paintings in the corridors; hence, we picked the six paintings which were rated with the highest score in both Salience and

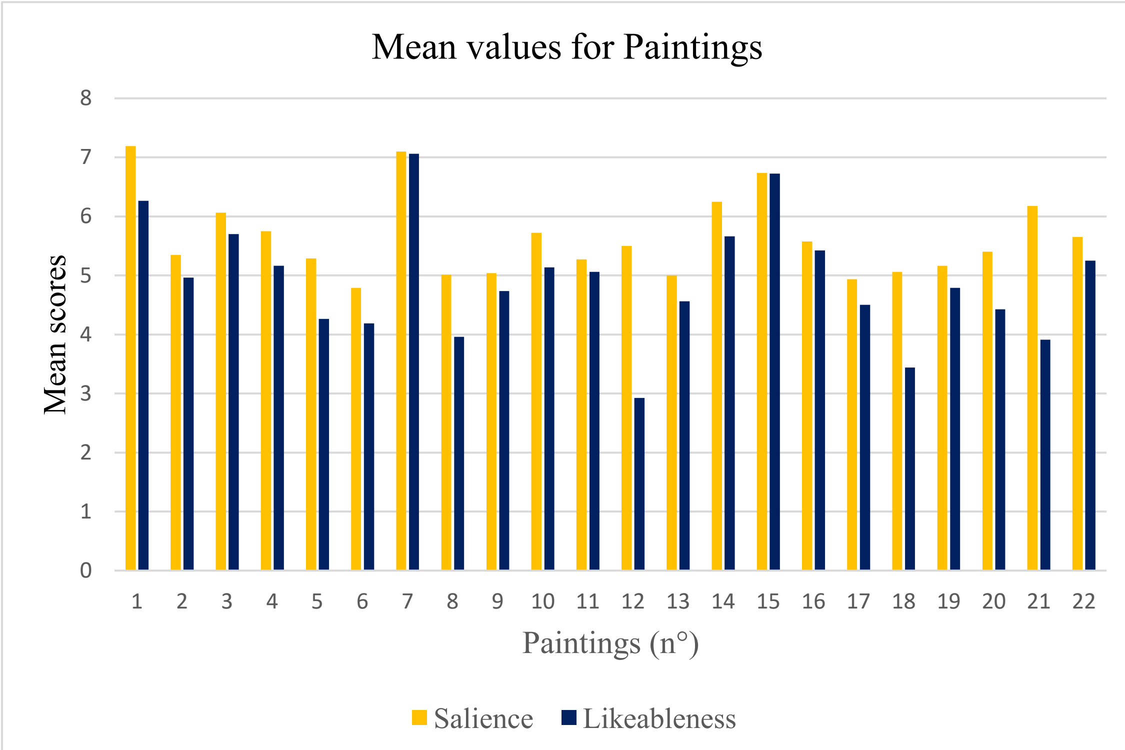


Figure 2. Graph showing the mean values for each Painting (from 1 to 22 on the x-axis) in terms of Salience (depicted in orange) and Likeableness (dark blue). The mean scores attributed by participants (from 0 to 8) are shown on the y-axis. The maximum possible score was 10, but the maximum mean value appeared to be 8.

Likeableness. Specifically, Paintings n. 1, 3, 7, 14 and 15 uniformly showed the highest score in both indexes (Table 2), whereas, for the sixth painting our choices were amongst Paintings n. 10 and 22, which were the paintings with the highest scores after the first five chosen. Our choice criterion was to consider the painting whose mean scores, added to the highest five scores, had the lowest standard deviation in both indexes.

We calculated the mean value of the five paintings with the highest scores in terms of both Salience and Likeableness, and then we recalculated the mean by adding as a six value both painting n°22 and painting n°10 (Table 3).

Finally, painting n° 22 had the lowest value of total standard deviation (considering both indexes) compared to the other painting.

Table2. Decrescent order of the scores for both indexes (Salience and Likeableness) for Paintings. The Paintings whose number is colored in pink are the ones with the highest scores for both indexes.

Painting (n°)	**Salience**	**Painting (n°)**	**Likeableness**
1	7.19	7	7.06
7	7.10	15	6.73
15	6.74	1	6.26
14	6.25	3	5.70
3	6.06	16	5.43
10	5.73	22	5.25
22	5.65	10	5.14

Table 3. Criteria from which Painting n°22 was selected for the experiment. Mean values considering both Salience and Likeableness criteria are reported, with the relative standard deviation values. The sum of both standard deviations for each painting is reported in the lower part of the table.

		Mean	**Standard deviation**
Salience	Top 5 values	6.67	
	Considering Painting n°22	6.50	0.17
	Considering Painting n°10	6.51	0.16
Likeableness	Top 5 values	6.28	
	Considering Painting n°22	6.11	0.17
	Considering Painting n°10	6.09	0.19
Sum of both standard deviations (Salience + Likeableness)			
	Painting n°22	0.34	
	Painting n°10	0.35	

Similarly, the same procedure was applied to select the nine statues (three in the main hall and the other six at the end of the corridors). We picked the nine statues with the highest scores in both Salience and Likeableness (Figure 3), whereas for the ninth statue to choose, our choice was among Statues n° 2 and 12. We adopted the same choice criterion that we had already used for Paintings (Table 4, 5), and finally, statue n° 2 had the lowest value of total standard deviation (considering both indexes) compared to the other statue.

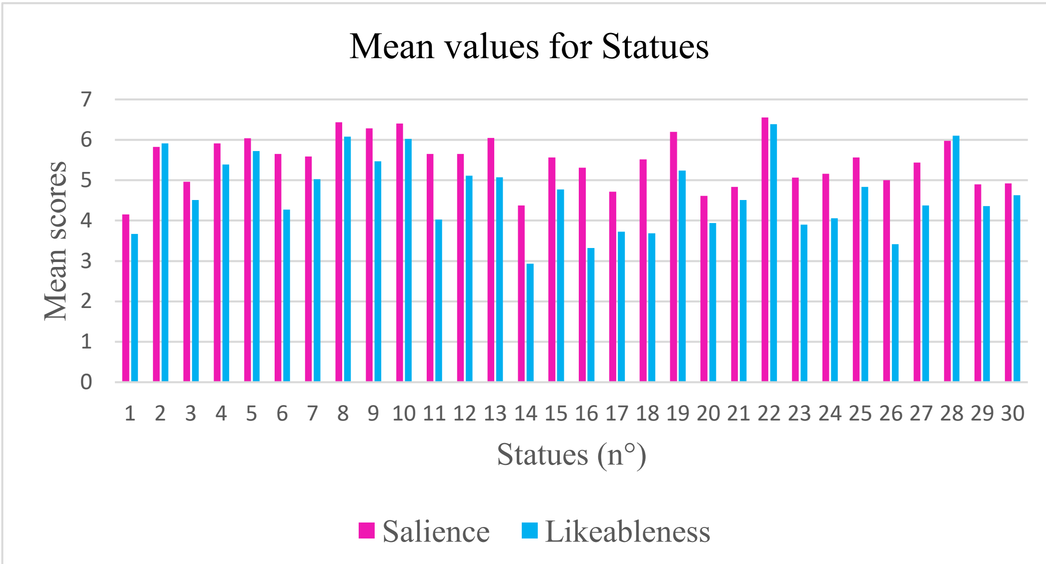


Figure 3. Graph showing the mean values for each Statue (from 1 to 30 on the x-axis) in terms of Salience (depicted in magenta) and Likeableness (clear blue). The mean scores attributed by participants (from 0 to 7) are shown on the y-axis.

Table 4. Decrescent order of the scores for both indexes (Salience and Likeableness) for Statues. The Statues whose number is coloured in red are the ones with the highest scores for both indexes.

Statue (n°)	Salience	Statue (n°)	Likeableness
22	6.55	22	6.39
8	6.44	28	6.10
10	6.40	8	6.08
9	6.29	10	6.03
19	6.20	2	5.91
13	6.05	5	5.73
5	6.04	9	5.47
28	5.98	4	5.39
4	5.91	19	5.24
2	5.83	12	5.11
6	5.65	13	5.08
11	5.65	7	5.03
12	5.65	25	4.84

Table 5. Criteria from which Statue n°2 was selected for the experiment. Mean values considering both Salience and Likeableness criteria are reported, with the relative standard deviation values. The sum of both standard deviations for each painting is reported in the lower part of the table.

		Mean	**Standard deviation**
Salience	Top 8 values	6.23	
	Considering Statue 13	6.21	0.02
	Considering Statue 2	6.18	0.04
Likeableness	Top 8 values	5.80	
	Considering Statue 13	5.72	0.08
	Considering Statue 2	5.81	-0.01
Sum of both standard deviations (Salience + Likeableness)			
	Statue n°13	0.10	
	Statue n°2	0.03	

In the end, 15 landmarks (9 statues and 6 paintings) were selected which depicted in (Figure 4). After the landmarks selection, we had to determine their position in the art gallery. To this end, a simple MATLAB script was written to assign the positions to paintings and statues randomly. Finally, the art gallery drawing resulted, as illustrated in Figure 5.

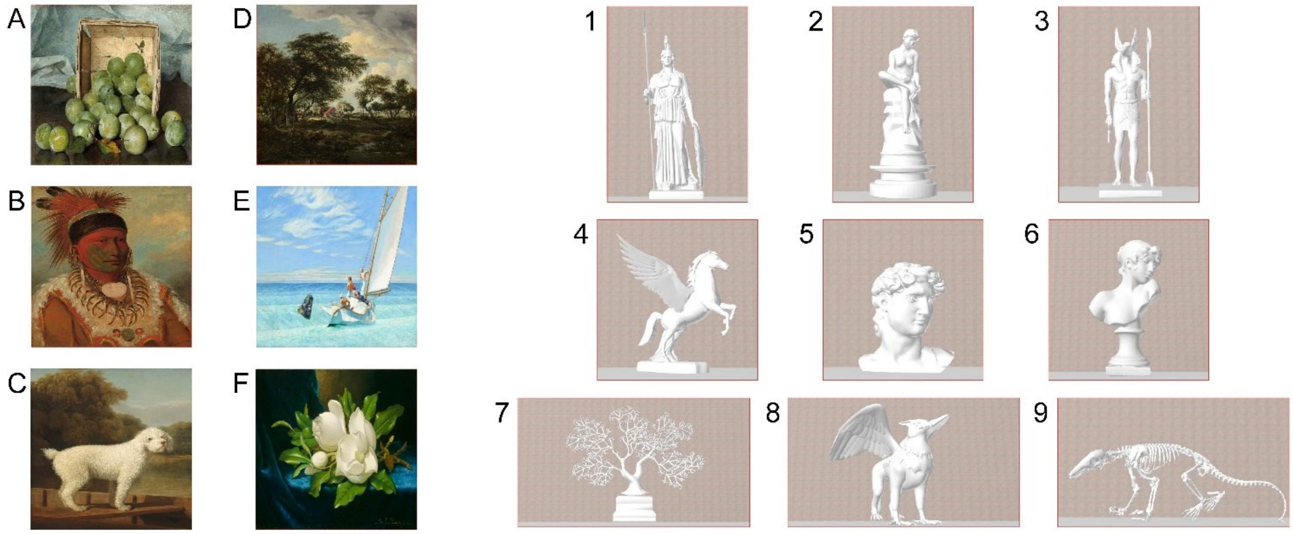


Figure 4. The selected landmarks. **Right.** The selected painting (from A-F). **Left.** The selected statues (from 1-9)

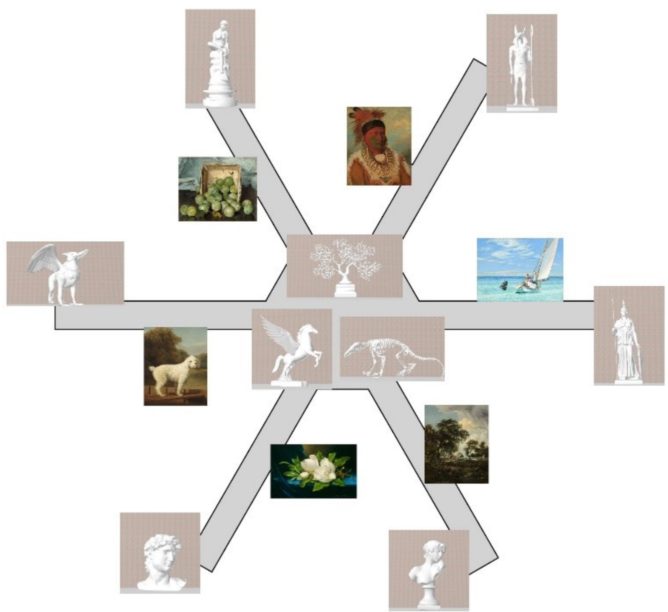


Figure 5. Position of the paintings and statues in the art gallery

So far, our research has included the planning and construction of an environment for the implementation of our experiment, and in the following, the assessment of individuals' differences in navigation in the designed art gallery maze is fully elaborated.

2.3.3 Subjects

In our behavioral study, a sum of 42 participants (24 females and 18 males) were assigned to the two separate study groups. The first group was given an explicit set of instructions, while the other group was assigned implicit instruction. The former group included 20 subjects (12 females and 8 males), while 22 subjects (12 females and 10 males) were designated to the latter. The mean age was 24.47 years (SD ± 2.49), and on average, our participants had completed 18.5 years of schooling, giving a standard deviation of ± 0.70. All participants were healthy, and none identified any mental or psychological disease. All of them were Italian natives and had a normal or corrected vision. As evaluated via the EHI (Edinburgh Handedness Inventory, 1971), all participants indicated that they were right-handed. Every subject provided written, informed consent for taking part. Our subjects consisted primarily of "La Sapienza" University students, and we wanted to limit our study group to students since we felt it would be better to have the most cohesive example with regards to intellectual and socio-cultural backgrounds and abilities as possible. Most of our subjects consisted of students attending a Master of Psychology, though some attended other degrees such as Art History, Engineering, Medicine, International Relationships, Nursery, and Dentistry.

3.3.4. Self-report measures

Individuals are somewhat diverse in terms of spatial abilities and orientation; these distinctions could be easily measured with questionnaires for self-report. A customized online questionnaire was generated with Google Modules comprising of three sub-sections and sent the day before the test to participants. The first part of the questionnaire included personal questions such as date of birth, name and surname, e-mail address, etc., which were obtained in compliance with the data security requirements. The remaining two sections encompassed three separate questionnaires, the Spatial Representation Questionnaire (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002; Pazzaglia & De Beni, 2001). The Spatial Representation questionnaire is a self-report questionnaire that evaluates the subjects' sense of orientation and spatial representation.

The questionnaire consists of 11 items that assess overall thinking abilities, including the spatial skills, such as the sense of direction, the knowledge and use of the cardinal points, the sense of orientation in buildings and in open spaces, and the preference for different types of spatial representations (survey, landmark-centered or route). Hegarty et al. have established a valuable self-reporting tool for assessing spatial environmental abilities, including a qualitative sense of direction (SOD) evaluation, a useful and accurate forecasting factor for different spatial abilities. They named their questionnaire "Santa Barbara Sense of Direction Scale" (SBSOD). When people are asked to judge their SOD as "good" or "bad," they make their decision based on spatial tasks like such as wayfinding paradigms, using maps for orientation, and giving and receiving route indications.

The SBSOD is made up of 15 items, which participants should rate from 1 to 7 (with 1 = I fully agree, and 7 = I disagree). The questions concentrate on analyzing personal spatial and navigational capacities, on personal preferences and experiences (Hegarty et al., 2002).

3.3.5. 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, as a quick turning to 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 training phase was designed for the subjects who were not familiar with playing video games.

The participants were all seated on a chair in front of the computer monitor at the same distance, and the light was held on so that everyone could read and follow the instructions outlined on an empty sheet of paper in A4 format. The lighting was switched off throughout the accomplishment of the task to facilitate vision on the computer monitor of the virtual-reality environment.

2.3.6. Experimental procedure

Our study consists of various phases, and participants were split into the two experimental, with each possessing their instructions. The experimental phases and their order are shown in Figure 6.

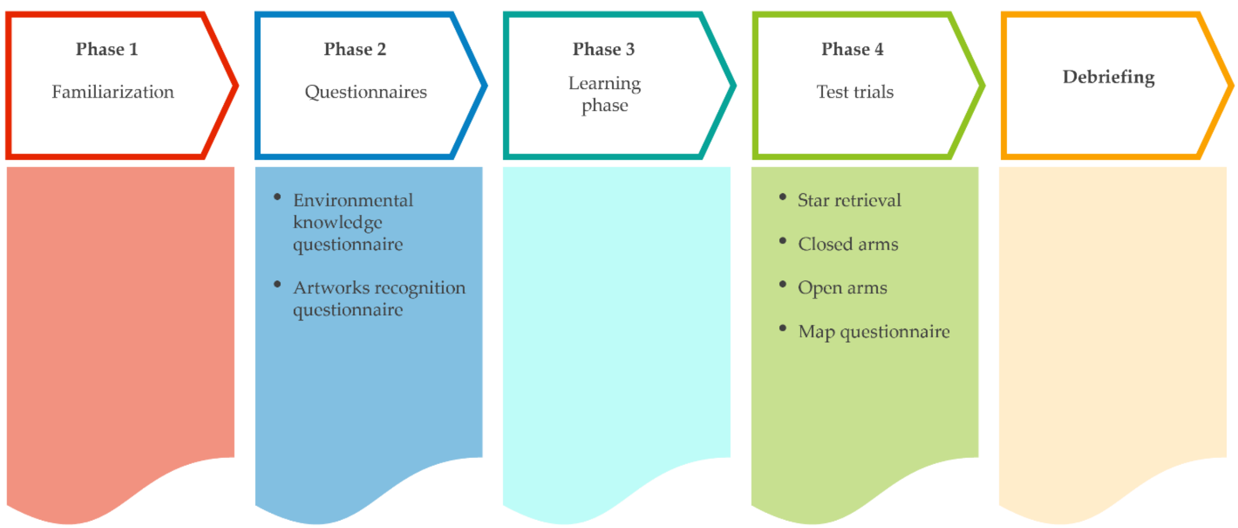


Figure 6. The experimental phases and orders.

2.3.6.1. 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 (Figure 7) with some exposed artworks, and received either “explicit” or “implicit” instructions according to their group. Explicit instructions were the following: “You should move freely in the gallery and appreciate all the artworks that you will see. You have ten minutes 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”. Implicit instructions were the following: “You should move freely in the gallery and appreciate all the artworks that you will see. You have ten minutes 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.

Figure 7. First-person view of the art gallery maze

2.3.6.2. 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?

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).

2.3.6.3. 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 six paintings and nine 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).

2.3.6.4. Place learning task

After the completion of the questionnaires, subjects performed a place learning task. Four golden stars were positioned at the end of four different arms (see Figure 8). 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 explicit 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 access the working and reference memory errors made in the test phase as two main dependent variables that characterize the subjects' performance on a radial arm maze (Kassa, Bajgar, Kuča, & Jun, 2020).

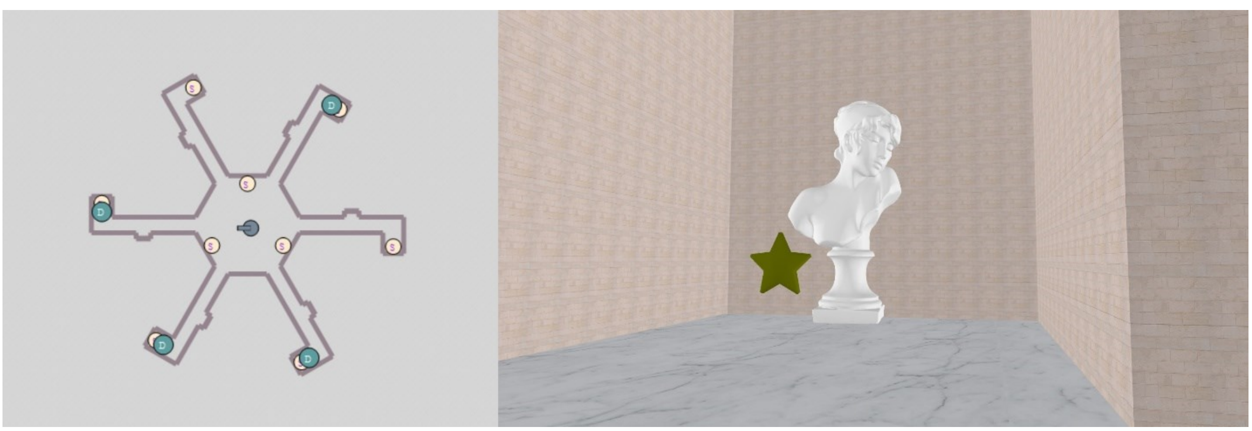


Figure 8. Left. Bird view of the position of the four stars (green circles and the letter 'D') at the end of four of the six corridors. **Right.** First-person view of the golden star

2.3.6.5. 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 Figure 9. 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 were 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.

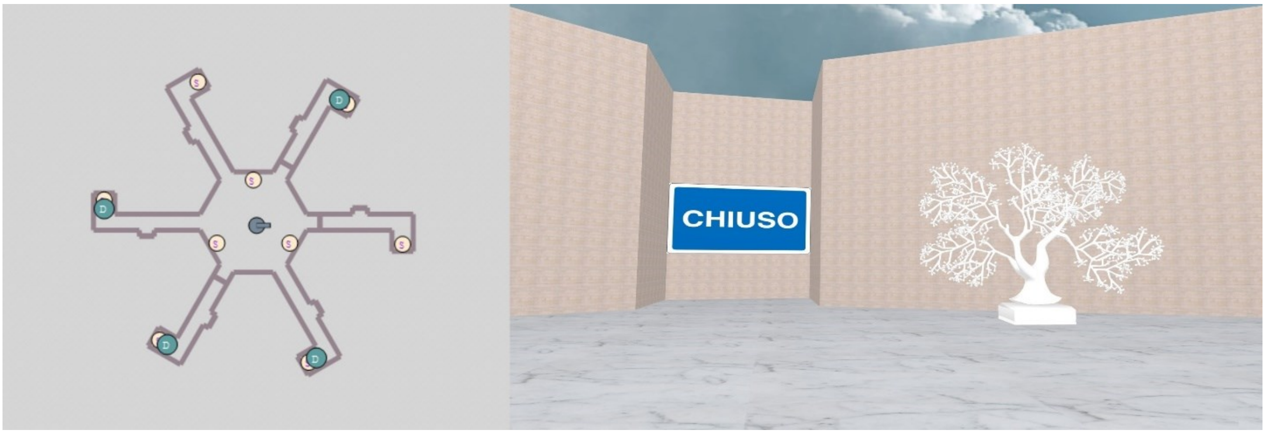


Figure 9. Left: Three of the six arms are closed and inaccessible. Two of them contain a star (green circle with letter 'D'), while the third one is empty. **Right:** Picture of one of the three walls with the "Closed" sign ('Chiuso' in Italian).

2.3.6.6. 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 challenging 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 section 2.3.8. Map test Analysis

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.

Performance scores

We collected performance scores from each subject's behavior:

- score at the environmental knowledge test, assessing the 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:

- reference memory errors: number of explored arms not containing a star.
- 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.
- 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.
- corrected working memory errors: as above, but without reaching the endpoint.

2.3.6.7. Debriefing

At the end of the experiment, participants were briefly explained the aim and rationale of all experiment and its different phases. Moreover, few more questions were asked, such as:

1. What do you think about your performance?
2. Did you adopt any strategy during the exploration of the environment?
3. Did you try to memorize and remember the position of the various artworks according to the different corridors of the gallery?
4. Did you try to pair and associate each painting with the corresponding statue in each corridor?

Such questions were useful for assessing and determining the performance of our participants in a more subjective way and for understanding the different strategies they have adopted to complete the trials.

The total amount of time that the subjects spent doing the entire experiment varied among 30-50 minutes.

2.3.7. Analysis of navigational paths

For every given maze trial (familiarization, learning, as well as the three test trials), the Maze Suite stored the route covered by each subject to a text file, and it constituted the subject's location information and direction at every instant of navigation. We utilized this file to classify the navigation key events and to measure a set of behavioral variables and ratings, as outlined below. The assessment was conducted out through a devoted MATLAB script in a semi-automated manner. The study began by dividing every trial into sections in which the participant is either situated in the center of the hexagonal hall or any of the six arms. As the participant begins exploration from the central area and has to travel back to the main hall when returning from one arm before pursuing another one, such subsection creates a list of segments where odd segments are inside the hall, and even segments relate to the arms.

Moreover, each arm segment was divided into a forward path (ultimately to the target) and a reverse path. The farthest point arrived in the arm was regarded as the target destination; a stopping duration close to the farthest point was utilized to differentiate the forward and the backward section. We needed to ensure the participant stopped when he arrived at the target destination location. As a matter of fact, even when the star was grabbed, some rapid participants do not pause at all. The program also was able to verify if or not the target was captured by considering the further position visited within the arm.

The central hall analysis was divided into “steady” and “moving” segments of activity and then split further based on which arm the participant was directed toward. Indeed, for the analysis, a new section has been created every moment the participant turns while walking and aims to visit a new arm. The main hall also was broken down into six segments equivalent to the six arms to make the analysis easier; in this manner, it was possible to determine the arm the subject looked at. Depending on the breaking down of the main hall into six segments, it was probable to decide when the participant changed his decision, the moment he crossed the junction boundary between two neighboring slices, this implied that he was moving for another arm that was separate from the one chosen initially. The program then rearranged the divisions by combining each forward portion of an arm visit with the last portion of each hall exploration, where the subject was already guided toward that arm; and connecting every backward segment from an arm to the immediately following arm exploration section, before the first route shifted. This finally produced the following set of segments (Table 6):

Table 6. An example of the subdivision of an exploration phase into discrete segments.

Segment type	Meaning
Reaching target	The subject is moving towards a target. The phase begins when the subject assumes a definite direction within the hall and ends when he reaches his destination within an arm.
Target reached	The subject stops at his destination within an arm. The destination is within the target area.
Unreached target	The subject stops at his destination within an arm. The destination is not within the target area, i.e., the subject has changed his mind before reaching the target.
Back from arm	The subject comes back from an arm towards the central hall.
Stopped in hall	The subject stops within the museum hall, possibly rotating his head around
Moving in hall	The subject moves within the museum hall, but he does not intend to go straight into an arm. He would rather stop or change direction at least once before entering an arm. There can be multiple consecutive phases of this kind if the subject repeatedly changes direction while moving. Each phase is associated with a given facing direction, i.e., towards a specific arm.

We determined a set of behavioral variables based on this classification that accurately defined the pattern of subjects' exploration during each cycle. Some computed variables alluded to the participant 's behavior in the entire trial, like the cumulative time spent in the maze, the cumulative distance traveled, and the mean speed. Various variables were tested within the time that the participant expended in the central hall after removing the sections of the path that were aimed directly from the hall to one arm and back from the arm to the hall. The remainder periods are better described as periods of decision-making, and they were subsequently categorized into periods of stop and walk. Such times were significant for the study as they represented the thought of the subjects regarding strategies and their next steps to fulfill the task. An overview of how our

MATLAB script analyzed each subject's navigational path is depicted in Figure 10. Furthermore, the resulting set of behavioral variables recorded during each phase of the virtual navigation is listed in Table 7.

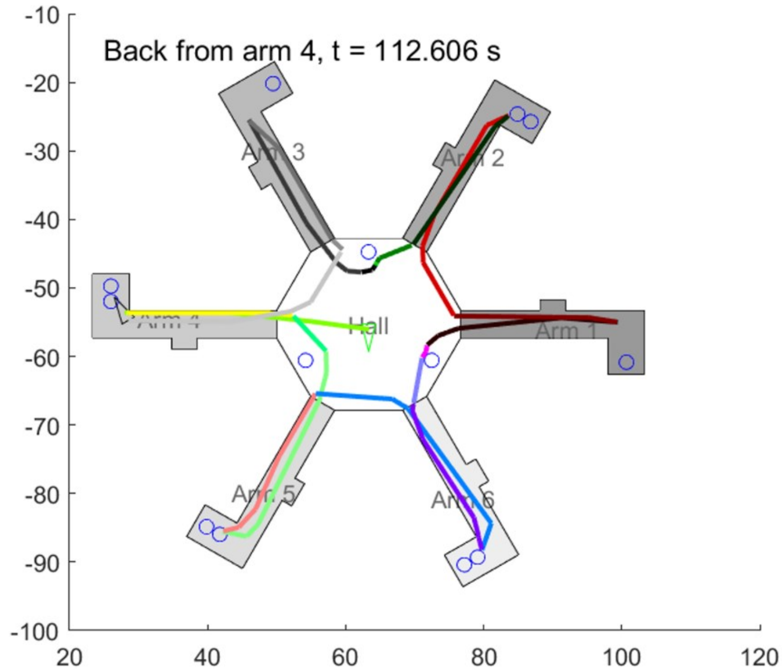


Figure 10. This picture represents the division of the maze in segments according to the subject's path, where each segment coincides with an event in navigation. Arms were enumerated from 1 to 6, starting from the right and then proceeding counterclockwise. Different colors are used to indicate the different enters in the arms and changes of directions.

Table 7. Behavioral variables recorded during navigation

Variable	Description
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).

Variable	Description
Time stopped in arm	Time spent in the arm without walking
Time moving to target	Time spent in arm when subject moves toward a target
Time moving back from target	Time spent in arm when subject back from a 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).

2.3.8. Analysis of navigational performance

We collected performance scores from each subject's behavior:

- Score at the environmental knowledge test, assessing the 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.

Moreover, we extracted several potential errors, aside from the different behavioral variables mentioned above, which participants may be made in the experiment, according to the trial context. Separately for the star retrieval, closed arms, and open arms tasks, we computed the number of committed errors by distinguishing different error types:

- Reference memory errors: number of explored arms not containing a star.
- 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.

- 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.
- Corrected working memory errors: as above, but without reaching the endpoint.

2.3.9. Map test Analysis

When the subjects were asked to complete the blank map, they had the option to discard off the action figures from the perspective they favored. As all 15 positions for the artworks were appended, the adjustment of the map from either of these perspectives could be completed.

Besides that, it was challenging to develop a specific correction method; as a matter of fact, due to the vast number of potential combinations, it was almost impossible to incorporate various parameters for a logical and extensible way of correction. Thus, we suggest our specific method of correction, dependent on certain mathematical hypotheses. We decided to split the overall map score into various sub-scores, all taking into account a distinct perspective of the requirements of the task. The configuration of the maze and the arrangement of all landmarks allowed us to segregate five essential characteristics, representing five possible, unique results. Also, we classified the various artworks dependent on their position within the art gallery: central statues (in the hall), paintings, and statutes in the arms (external position). The five scores account for five aspects relative to the correct completion of the map.

1. Score for the sequence of the statues in the arms, Irrespective of their position toward other artworks. The statues placed at the end of the six arms form the vertices of a regular hexagon. A specific sequence of icons could be obtained, beginning from any arbitrary statues and proceeding in the clockwise or counterclockwise direction (Figure 11). The "path" formed by the sequence of the statues which correlates to the perimeter of the hexagon as in the case of a correct sequence of statues.

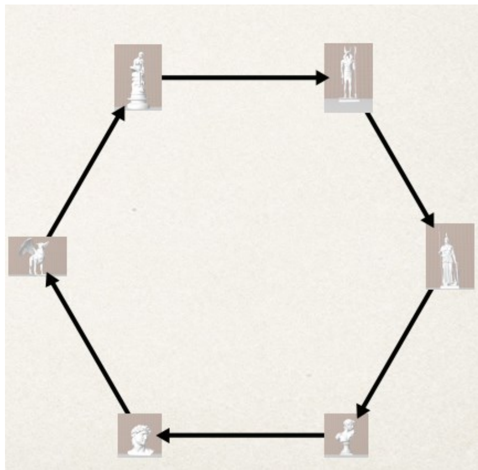


Figure 11. Correct sequence of the statues positioned at the end of the six arms in the museum.

Besides this, if one participant has swapped the position of two or more statues, a different sequence of statues is determined. In this scenario, reviewing the wrong sequence creates a much more complicated path than the initial one (Figure 12).

The further a statue is placed from its correct position, the longer the resulting path will be. Given that the distance connecting two figures might be visualized as different segments (or sides of the regular hexagon), we decided to attribute three different scores based on the correct attribution of the relative positions. The general rule is that the longer the segment connecting the two statues is (meaning that that statue has been positioned very far from its original location), the lower the score would be. The overall score is determined by the number of all the created segments, divided by 3 (with the maximum score being 12). During the first four categories, we agreed to divide the score by 3, so the original final score would then be 36. Nonetheless, as long as we chose to measure our scores equivalently for the final score, we decided to divide the overall score of 36 by 3 ever since the fifth probable score (the one related to the pairing among both statues and paintings) is just 12.

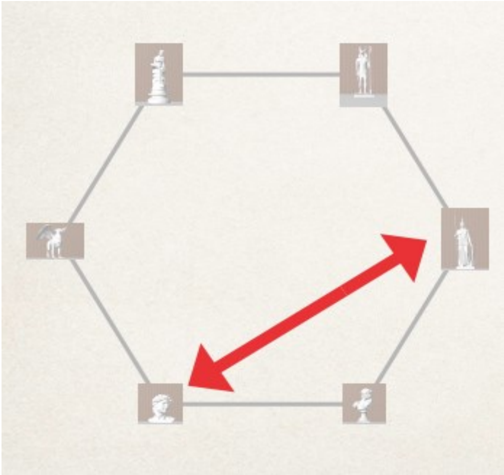


Figure 12. Example of an incorrect sequence of statues. The order of two statues is swapped, generating a more intricate path for correction.

Under those conditions, the division by 3 offers a homogeneity of our five scores. Three potential scores compared to the first aspect are shown in Figure 13.

This correction technique's significant benefit is that it is independent of the beginning point, where the researcher wants to correct the map. It would generate a similar final score beginning from any statue and proceeding in every path. In Figure 14 an example of the sequence scoring is illustrated.

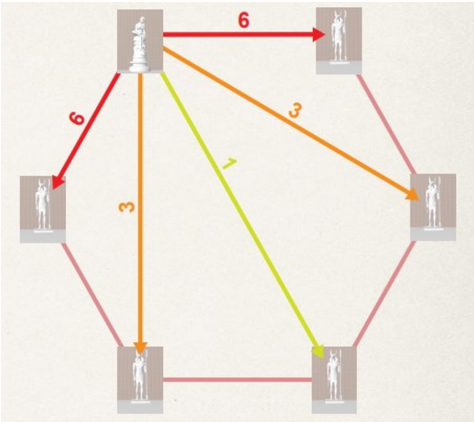


Figure 13. Scores attribution. When the correct position of a statue respectively of the neighboring ones is maintained (as for example, the statues of upper left and right), a score of 6 is attributed (red line). A score of 3 (orange line) is given when the distance is longer than in the previous condition, but not as long as the furthest distance, which is scored with 1 (olive line).

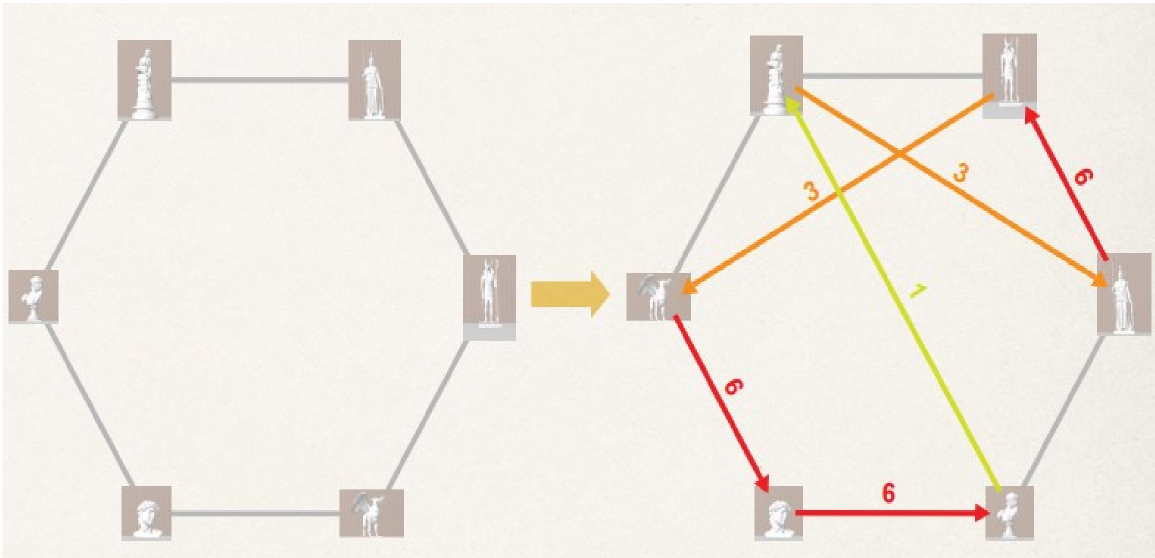


Figure 14. On the left, the correct position of all statues in the six arms is displayed. On the right, there is an example from a subject who made few errors. Specifically, the distance between the statues upper-right and middle-right is correctly maintained and scored with 6. On the other hand, the distance between the statues upper-left and middle-left is not correct (here positioned in the lower-right vertex) and, since it is the furthest possible distance, it is scored with 1. A score of 3 is given, for example, considering the distance between statues upper left and middle right (which was switched with upper right).

2. Score for the sequence of the paintings in the arms, independently from their position towards the statues in the arms and in the central hall. In this case, it is possible to apply the very same precisely similar method mentioned for the statues, leading to another maximum score of 12.

3. The score for the correct matching between each central statue and the two statues in the adjacent arms, Apart from the same-armed painting. In fact, each central statue is close to the two neighboring arms, with the relative artworks. The further statue's actual location compared to the subject's assigned position is, the lower the score will be (Figure 15). This method is applied to the three central statues, but the overall score is provided by the total of the collected six values (every score for each statue compared to the central one), divided by three. The maximum possible score is 12.

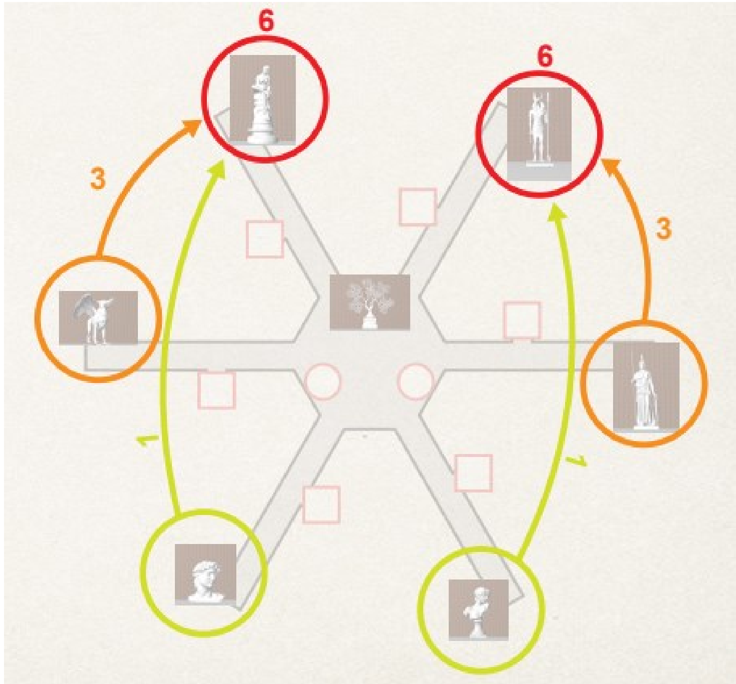


Figure 15. Position of the six statues relative to the location of the central statue "Tree". The statues upper left and upper right are correctly positioned (+6 score), but the middle left and right if swapped with lower right and upper right, respectively, are attributed a score of 3. A score of 1 is provided in the lower right is switched with upper right, which is the furthest possible location.

4. Score for the correct matching between each central statue and the paintings in the adjacent arms, independently from the statues in the same arms. The same mechanism explained in point 3 is applied here.

5. The score for the correct statue-painting pairings, Regardless of their place in the arms. We decided to assign a score of 2 by each correct pairing of statues and paintings, and a score of zero for each incorrect pairing. Again, the overall possible score is 12.

The total amount of the five separate scores displays the actual overall score that can be the maximum of 60. By transferring the final score into hundredths (percentages), the percentage of correct execution of the map can be obtained (total = 100 percent). This score is termed as a "similarity score" since it is the percentage of similarity to the original map.

By creating a MATLAB script, we automated the whole process for calculating the final score for each subject. To use that function accordingly, the map must be rotated in any dimension until the typical triangle given by the central statue locations is viewed with its vertex at the top (see Figure 16).

To reach the final score comparative to each subject's performance, the verbal tags ascribed to each artwork should be listed in the script following this order (see Figure 17).

In the end, MATLAB generates a number that corresponds to the overall percentage of similarity comparative to the participant's performance.

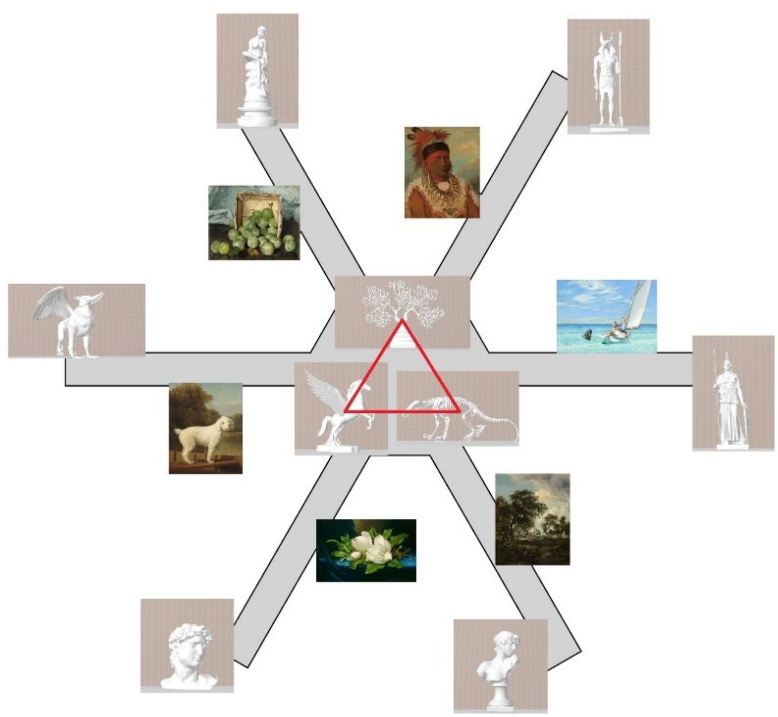


Figure 16. This picture shows how to position the map with the subject performance for the further final score calculation. The central triangle should be visualized as depicted on the left.

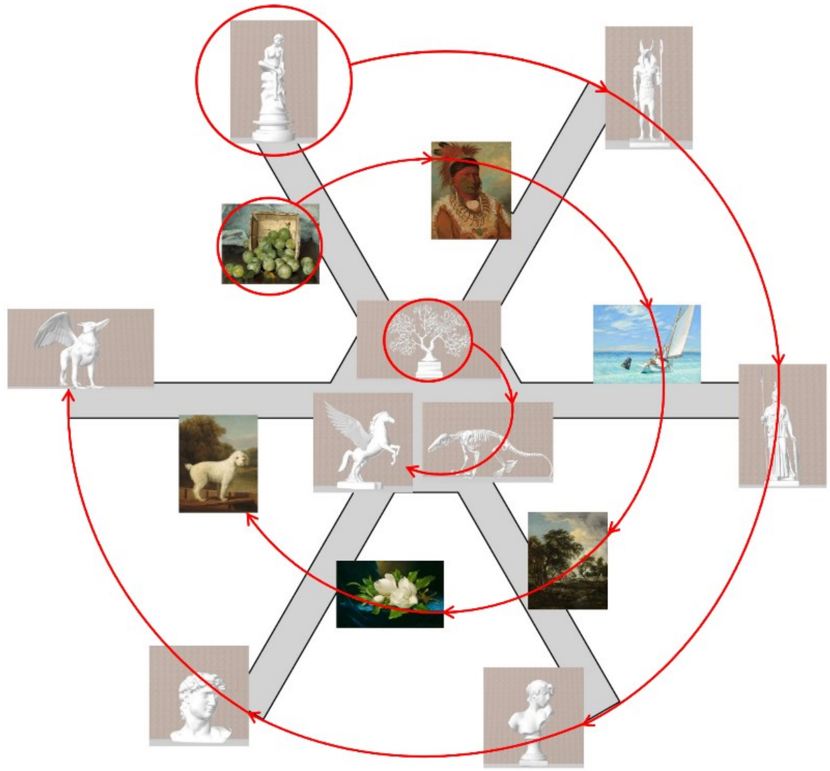


Figure 17. Order in which the artworks should be inserted in the MATLAB script to generate the final score. The analysis starts from the statues in the arms (from statue upper left, and then proceeding clockwise), and it is followed by the paintings (starting from the upper left, then proceeding clockwise). In the end, the last analysis is the one regarding the central statues, starting from the Tree and proceeding clockwise.

2.4. Results

2.4.1. 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; therefore, we analyzed the data with non-parametric statistical tests. Specifically, we performed a two-sample Wilcoxon signed-rank test for analyzing the subject's navigational abilities and behavioral variables between the Explicit instruction group and the Implicit instruction group. The analysis was performed using MATLAB (2017b).

2.4.2. Navigational Performance Scores

To assess whether the type of instruction given (Implicit vs. Explicit) 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 8, 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 explicit and implicit groups, but painting to central score in explicit group with an average of 79.62% is significantly higher than the implicit group with an average of 64.55%. Also, there is a significant difference in arm pairing between the explicit group (average = 60.31%) and the implicit group (average = 28.57%).

Table 8. Comparison of the Navigational Performance Scores (Explicit instruction vs. Implicit instruction groups)

	Explicit Mean	Implicit Mean	P-value
Santa Barbara Sense of Direction Questionnaire	58.09	61.90	0.412
Spatial Representation Questionnaire	46.40	48.06	0.781
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**

Table 9 reports the results relative to the analysis of the number of errors. Wilcoxon signed-rank test indicated that the mean of the working memory errors and reference memory errors in the implicit group were significantly higher than the ones of the explicit group for the first and the second trial of the test phase. Moreover, we could not find any significant difference in corrected errors for all test phase trials.

Table 9. Comparison of subjects' errors in the three test trials (Explicit instruction vs. Implicit instruction groups)

	Star retrieval trial			Closed arms trial			Opened arms trial		
	Mean Explicit	Mean Implicit	p-value	Mean Explicit	Median Implicit	p-value	Mean Explicit	Mean Implicit	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

2.4.3. Behavioral variables

2.4.3.1. Familiarization phase

As shown in Table-10 during familiarization, those subjects provided with explicit instructions 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 explicit 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 explicit group evidently explored the environment paying more attention than the implicit group.

2.4.3.2. Learning phase

During the learning phase (Table 10), the Explicit instruction group spent more time in the environment, with an average time of 223.59, and subjects were in general, slower, compared to Implicit group's participants, with an average time of 155.40. Moreover, Wilcoxon signed-rank test showed that the explicit 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 implicit 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.

Table 10. Subjects' behavior during familiarization and learning phases

	Familiarization Phase			Learning Phase		
	Mean Explicit	Mean Implicit	p-value	Mean Explicit	Mean Implicit	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

2.4.3.3. Test Trials

In the star retrieval and closed arm trials (Table 11), subjects who received explicit instructions spent more time stopped in the hall (average= 15.45 and 23.36), compared to the implicit group (average=4.25 and 14.92). In the closed arm trial, subjects who received implicit instructions cover a significantly longer distance in the hall (average= 35.19) compared to the explicit group with an average of 15.84. These results indicate that, in contrast to the familiarization and learning phases, that the explicit group traversed more in the central hall, in the test phase the implicit group cover more distance than the explicit group. Furthermore, the average number of stops in the hall and cumulative turn when the subjects are stopped in the hall for the explicit group, in star retrieval trial are 7.38 and 594.76, respectively, which are significantly higher, compared to the implicit group with the average of 3.80 and 222.23. A difference was also found in the time stopped in the arm for the explicit group with an average of 12.20 compared to the implicit group, with an average of 6.17 in maze3.

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 on moving to the target and back from the target in the implicit group is significantly higher than the explicit 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 (the open-arms trial), but the subjects' walking time in the hall and distance in the hall is very close to being significant between explicit and implicit groups (p= 0.051 and p=0.051 respectively). In the open-arms trial, the implicit group tends to spend more time for walking in the hall with an average of 4.53 than the explicit group with an average of 2.41and also the traversed distance by the implicit group with an average of 26.25 is much higher than the explicit group with an average of 13.91.

Table 11. Subjects' behavior during test phases

	Star retrieval trial			Closed arms trial			Opened arms trial		
	Mean Explicit	Mean Implicit	p-value	Mean Explicit	Mean Implicit	p-value	Mean Explicit	Mean Implicit	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

2.4.4. Effect of explicit and implicit 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 (Figure 18).

In the familiarization phase, both explicit and implicit group presented a ratio >1 for distance covered and time spent, meaning that both groups preferred to navigate the 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 implicit group presented a statistically higher ratio both for distance and time compared to the explicit group. This means that implicit 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 explicit group. The statistical tests showed again a significantly higher preference for the external region in the implicit group. These results imply that in closed arms and opened arms trials, subjects presented with explicit instructions spent more time navigating the internal region of the hall compared with the external one, while subjects from implicit groups still preferred the external region over the internal one.

In Figure 19, for better clarity, we illustrated the navigational routes of three subjects from each group who received implicit and explicit instruction.

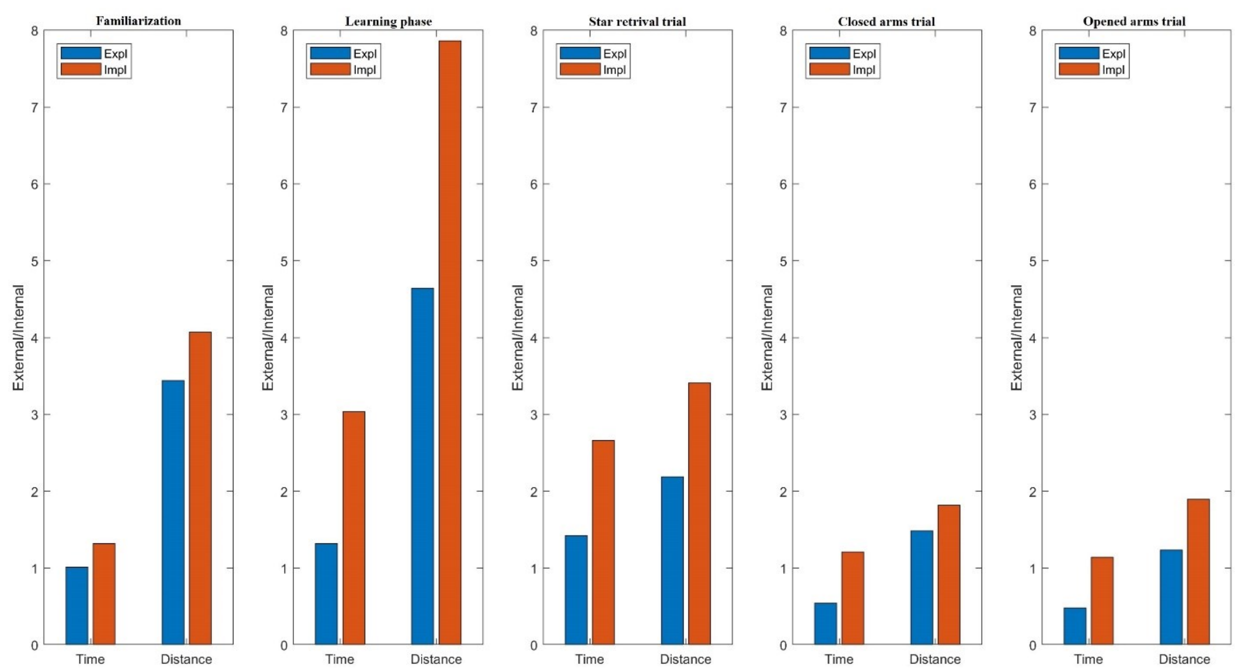


Figure 18. The effects of the implicit and explicit instructions on the navigational preferences. The ratio of time and distance in the external region to the internal for each group

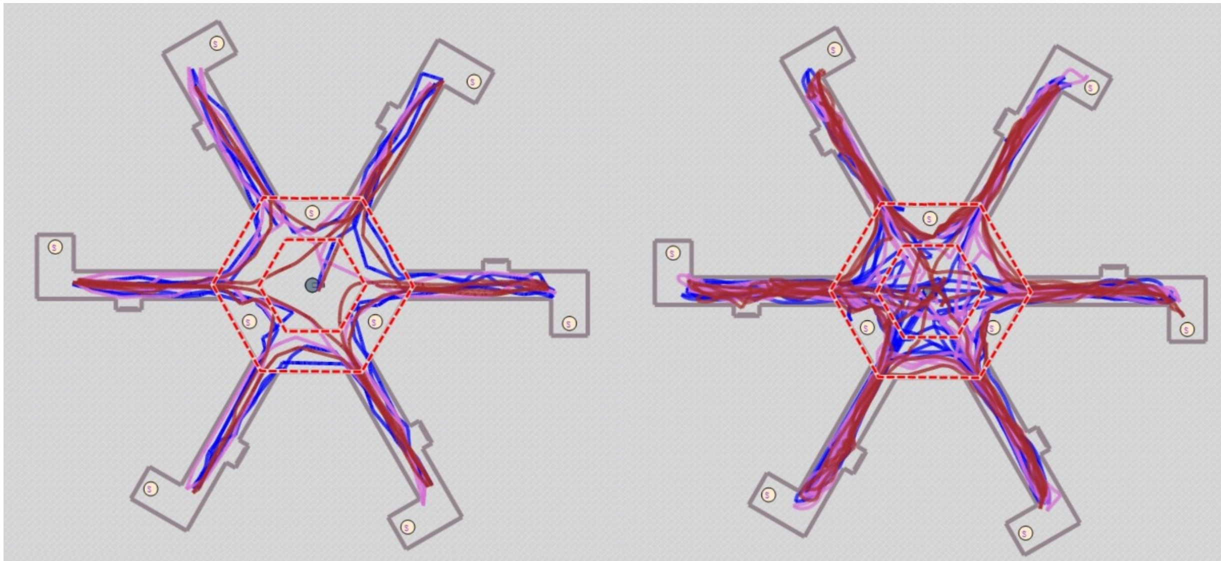


Figure 19. (Left). The navigational routes of three subjects from the implicit group (Right). The navigational routes of three subjects from the explicit group

2.5. Discussion

Previous studies on human navigation (Auger, Mullally, & Maguire, 2012; Auger, Zeidman, & Maguire, 2017; Cornwell, Johnson, Holroyd, Carver, & Grillon, 2008; Etchamendy & Bohbot, 2007; Hartley, Maguire, Spiers, & Burgess, 2003) have not investigated in detail which behavioral variables distinguish both explicit and implicit navigators in the context of spatial mazes, and thus which spontaneous exploration strategies are adopted according to the task demands. The novelty of our study resides in our experimental paradigm: 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.

Another aspect that distinguishes our study from previous ones (e.g., ((Ferguson & 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 explicitly informative or not. The results show that subjects who receive explicit instructions about the task demands generally perform better than participants who only have access to implicit instructions.

The questionnaire and map test show the participants who received the explicit 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 explicit groups 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 implicit group. The errors analyzed during the test phase show that the subjects who received the implicit 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 could not learn the maze environment well and showed a weaker performance at the testing phase. The most exciting results were achieved an in-depth 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 explicit 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 explicit group spent more time in the familiarization and learning phase, and they are much slower than the implicit group because of the given instruction. The outcome is that the explicit group spent more time in the environment and stopped in the main hall, they covered a long 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.

Nonetheless, we could not find significant differences for the total time in the test phases, but the results clearly show that the explicit group was surprisingly faster than the implicit group in the test trials. The spontaneous strategies changed during the test trials, with participants from the explicit learning group traveling less, but spending more time in the main hall than the other group. It seemed that explicit 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 implicit 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 towards details during familiarization and learning phases.

As already mentioned, the explicit 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 explicit and implicit group when they move back and forth from the target in the familiarization and learning phase, while the subjects who received the explicit instruction spent significantly less time to move back and forth from the targets in the test phase, and they perform much faster than the implicit group. This finding shows that, during navigation, subjects in the explicit group made their decision based on the available spatial information of the main hall while, on the other hand, the implicit group tended to move straight-forward to the targets without changing direction or being in doubt during move towards the arms.

In this study, we also directly addressed the effect of given instructions (explicit and implicit) 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 explicit instructions surprisingly spent more time and also explored more the internal area of the central hall, whereas the implicit group tended to navigate in the external part of the central hall.

2.6. Conclusion

We believe that the current results provide compelling 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 (explicit and implicit). 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.

Brain Dynamics During Landmark-Based Learning Spatial Navigation

3.1. Abstract

Spatial navigation is one of the basic and vital functions in both animals and humans for seeking food, get to work or university, avoid prey, and safely return home. During spatial navigation, an individual for determining and following a specific route to a goal location can use several cue sources such as landmarks, beacons, path integration etc. Spatial navigation is inherently a complex skill that involves integrating visual, proprioceptive, and vestibular inputs and includes a variety of cognitive processes such as visual perception, learning, memory, and spatial orientation. Several studies have investigated how the brain encodes and retrieves environmental information to lead humans and animals to accurate navigation. It is worth mentioning that the basis of human spatial navigation research and our knowledge of the cognitive, behavioral, and neural mechanisms back to animal research. Based on decades of research in rodents and humans, the researchers have been explored that several brain regions such as hippocampus, medial temporal lobe, precuneus, retrosplenial cortex, etc., are involved in spatial navigation. Although human spatial navigation has been extensively researched during recent years, there is still a lot of ambiguity in our knowledge regarding brain function and dynamics during navigation. Hence, in this chapter, we aim to explore brain dynamics and neurophysiological activity during spatial navigation. More specifically, we intended to figure out how navigational-related brain regions are connected and how their interactions and electrical activity vary according to different navigational tasks and environments. This experiment consisted of two stages: learning phase and test phase. A virtual nine arms radial maze was designed and furnished like an art gallery that was used for landmark-based spatial navigation. The main task of the experiment was finding and memorizing the position of some goals within the environment during the learning phase and retrieving the spatial information of the goals during the test phase. We recorded EEG signals of 21 subjects during the experiment, and both scalp-level and

source-level analysis approaches were employed to figure out how the brain represents the spatial location of landmarks and targets and, more precisely, how different brain regions contribute to spatial orientation and landmark-based learning during navigation.

3.2. Introduction

During navigation, orientation infers to the knowledge one has about a given direction or heading in reference to the surrounding environment; essentially, being oriented with one's environment is essential for successful navigation. For instance, in a case where one gets lost in an unfamiliar location such as a park, being conversant with one's orientation can be essential in assisting one navigate their way out or identify which direction to take next. As stated by (Wang & Spelke, 2000), during a navigation process, a sense of direction is essential in understanding and identifying the spatial connection between the numerous space, and this can also improve internal representations of object location.

Over the past few years, numerous approaches have been investigated to explore the role of visual landmarks in spatial navigation and memory in humans and rodents. From a general perspective, animals and humans use landmarks in finding their way through and determining where they are heading.

3.2.1. Definition of landmark in spatial navigation

The term landmark is referred to various forms of visual information within an array of contexts. Landmark is, in most cases, used when inferring to a well-recognized or visual salient monuments or structures, since such are always fixed in space, they are deemed to be essential for navigation (R. A. Epstein & Vass, 2014). Landmarks can be recognized in various shapes such as single and discrete objects such as statues and buildings and extended topographical features such as valleys, ridge, or arrangement of structures at an intersection. Based on the specific roles played during navigation, it becomes possible to categorize landmarks into four groups, including (1) visual objects acting as a beacon (marking of a nearby or precise location), (2) the second phase includes visual objects providing information about a contemporary heading orientation. (3) Visual objects being implemented as associative cues for eliciting navigationally pertinent, appropriate data, and the last group is comprising of visual objects acting as a landmark issued by a reference frame for the spatial and encoding data.

Modestly, a single object within a specific environment can serve as a navigational landmark by acting as a beacon (object representing a nearby location, or one that acts as a target location in itself) (Waller & Lippa, 2007). For instance, Eiffel Tower can represent a beacon when indicating the location in Paris. Similarly, in a built-up environment, a church tower's spike that protrudes from a surrounding building can also represent a beacon possibly used in locating the church. Specifically, the beacon can act as a form of visually guided navigation dependent on a negligible allocentric reference frame. Ideally, this would also comprise monitoring a self-location with reference to a single cue, regardless of the available information within the same environment (Chan, Baumann, Bellgrove, & Mattingley, 2012).

In as much as a landmark infers a discrete object within an environment, the boundary or the extended surface of geometry can nonetheless provide essential navigational information (Cheng, 1986; Lee & Spelke, 2010). In a natural environment, this can represent contours of the mountain lines or even the shoreline, whereas in artificial environments, this might be represented by a structure of a room or the sides of a much larger building. The boundaries and geometry of extended surfaces can also provide essential data used in navigation. The boundaries or geometry of the extended surfaces, as well as that of the intrinsic geometry of more discrete object locations, can also operate as many unique landmarks through providing a schema or reference frame for encoding spatial data. Additionally, the geometry of an object can also provide orientation and directional information for localizing oneself in an environment (Cheng & Newcombe, 2005).

In human spatial navigation researches, the wayfinding strategies while the destination is not directly visible can be categorized into two main groups: landmark-based navigation (or piloting) and path integration (or dead reckoning) (Goldstein, 2009)

Similarly, path integration and landmark-based piloting can function in concert during navigation (Kalia, Schrater, & Legge, 2013), in which the path integration is implemented in keeping track of one's position while exploring a new environment, and landmark-based piloting is used in re-establishing or re-calibrating quantities in an environment that is familiar (O'keefe & Nadel, 1978).

3.2.2. Landmark-based navigation

In order to accomplish landmark-based piloting, one will need four cognitive mechanisms that will aid various components of the strategy(R. A. Epstein & Vass, 2014). Firstly, the landmark recognition mechanism in identifying landmarks within a sensory horizon, second, an orientation/ localization mechanism that implements sensory data when determining an individual's current position. Thirdly, an encoding mechanism and retrieving long-term spatial knowledge over the locations of different points of interest are likely to act as navigational goals. Lastly, a route-planning mechanism that implements spatial information in planning a route to one's destination. In the following, the first three cognitive mechanisms which play a crucial role in our experiment are explained briefly.

3.2.2.1. Landmark recognition

Landmark recognition (identification of landmarks in the presence of one) is the first step in landmark-based piloting. In theory, the brain is most likely to use a general-purpose object identification system in solving problems. Although, it seems the brain relies on a more specialized landmark recognition mechanism. Equivalent in numerous ways to a more specialized mechanism that supports face recognition. The primary neural locus of such a mechanism is identified as the Parahippocampal Place Area (PPA) (a region in the collateral sulcus close to the lingual boundary) exhibiting strong functional Magnetic Resonance Imaging (fMRI) response when subjects perceive the environmental stimuli such as streets, buildings, landscape and rooms (R. Epstein, 2005; R. Epstein & Kanwisher, 1998). By comparison, the PPA would only respond weakly when subjects see ordinary objects such as tools, appliances, and vehicles at a glance. Notably, PPA exhibits a strong preference for an environmental stimulus even when subjects passively view stimuli without the need to perform any explicit navigational task (R. Epstein, Harris, Stanley, & Kanwisher, 1999).

3.2.2.2. Landmark localization

Using landmarks in determining where a person is and which direction he/she is facing or heading is the second step during landmark-based navigation. In the second step, a person not only should identify a place he is looking at but also need to localize and orients himself within a given spatial framework with the potential of extending beyond a contemporary horizon. Identification and orientation/ localization acts as a theoretically distinct operation. For instance, a tourist in Rome might be able to identify the Colosseum and St. Peter's Basilica without being able to use that information to figure out where they were in the city or which direction they were facing. Numerous evidence lines bring to the discussion that the PPA is never an essential locus in orientation or localization. Instead, such an operation is basically supported by medical parietal region identified as the Retrosplenial complex (RSC) comprising of a Retrosplenial cortex and a more subsequent territory besides a parietal–occipital sulcus (R. A. Epstein, 2008; A. S. Mitchell, Czajkowski, Zhang, Jeffery, & Nelson, 2018). Similar to the PPA, the RSC activates during passive viewing scenes; however, such a response is highly enhanced whenever scenes are accustomed locations, in such reference, bringing about a role in connecting a visual perception to a long-term knowledge (de Landeta, Pereyra, Medina, & Katche, 2020)].

The RSC mainly is involved in identifying the location of an individual and the manner in which one has been oriented in the spatial border environment, on the other hand, PPA should be primarily concerned with the analysis scene or landmarks (R. A. Epstein, 2008; R. A. Epstein, Parker, & Feiler, 2007; Smith, Barredo, & Mizumori, 2012).

3.2.2.3. spatial knowledge–landmarks

The third step in landmark-based piloting is accessing knowledge over spatial locations of other areas of interest that serves as a navigational goal. As already mentioned, some of the long-term spatial information might also be encoded with the RSC that distinguishes between locations and might also encode data over the directional relationship between locations. Moreover, a cognitive map is another way of representing spatial information, which can act as a representation of Euclidean coordinates of a landmark with other navigational points that are deemed analogous to a physical map (Gallistel, 1990; Sato, Sakata, Tanaka, & Taira, 2006). Various studies bring to the point that the Medial Temporal Lobe (MTL) regions are likely to instantiate such a map. Such an idea had been initially proposed by (O'keefe & Nadel, 1978), founded on the place cells discovery in rodent's hippocampus.

3.2.3. Brain function during landmark-based navigation

Studies on electrophysiological and imaging have since brought to book that the wayfinding relies heavily on landmarks and their associated positions (Jansen-Osmann & Wiedenbauer, 2004; Janzen & Jansen, 2010; Wegman, Tyborowska, & Janzen, 2014). For instance, (Janzen & Jansen, 2010) illustrated the participation of Para-Hippocampal Gyrus in both object and scene recognition. Such brain regions displayed a higher activity once the objects were countered at appropriate locations as compared to those termed as irrelevant. Similarly, an EEG study by (Weidemann, Mollison, & Kahana, 2009) did explore the electrophysiological basis of recognizing objects in a virtual-reality taxi driver game where participants were expected to search for passengers (neutral stores) and stores (non-targets or targets) during a virtual-navigation in simulated towns with simultaneous recordings of EEG. In the following study, the obtained results illustrated a theta activity that had been reliably distinguished between a non-target, target, and neutral store views. Additionally, the frontal-theta oscillatory power had been considerably lower for the target stores indicating at the same time a more frontal engagement (attention) on the target stores. Such findings did support an involvement notion of a theta band in object identification and classification.

In the fMRI study was implemented by (Auger et al., 2012), they find out that the Parahippocampal cortex is responsive to visual-spatial features of landmark, whereas the Retrosplenial cortex (RSC) is engaged when subjects see landmarks with a more permanent location within the ambiance. In their other study (Auger, Zeidman, & Maguire, 2015), they designed a virtual environment and put landmarks where some of them maintained in fixed positions on all learning trials, while others changed location from one trial to the next. The fMRI results indicated that as subjects came to understand how to distinguish the permanent landmarks from the transient landmarks, the direct RSC responses reflected on their knowledge of such a difference. The activation in the hippocampus had been seen towards the end of every learning period whereby such activity had been related to the participants' understanding of the permanent locations. Communication between the hippocampus and the RSC had also been heightened, affecting the role of new environment mappings. In this respect, the RSC appeared to code the stability of features within the environment and providing this as an input to the hippocampus.

3.2.4. Electrophysiological Research on Spatial Navigation

Electrophysiological studies provide the opportunity for researchers to monitor the human brain's neuronal activities during spatial navigation tasks.

The oscillations are always formed in the brain, whereby the synchronous activity of neuron populations brings about largely negative and positive fluctuations in voltage. Theta band (activity in 4-8 Hz range) is a brain oscillatory which becomes elicited during specific cognitive function (Caplan et al., 2003). This is most cases linked with a successful memory encoding, and it is also involved in navigation. In the spatial navigation studies by (Araújo, Baffa, & Wakai, 2002), the researchers utilized magnetoencephalography (MEG) for monitoring brain oscillations. Such investigations found out that an increase in theta band during movement periods within a virtual environment as compared to the controlled conditions. Although their study did not find theta activity to be linked to a specific event (Bischof & Boulanger, 2003), they used a scalp EEG and found out the increase in theta oscillations while new spatial information was acquired. The following studies brought about intracranial recordings among the epileptic patients and noticed a specific strong increase in theta during integration between the motor planning, such as identifying a target location, and sensory data such as the optic flow during movement. It is also important to note that a passive viewing of movement within a virtual environment elicited a slight increase in theta band activity (Araújo et al., 2002).

The study by (Klimesch et al., 2004) states that oscillations can result to “phase locking” or “resetting”, and as a result, this builds a larger wave in creating a positive and negative component in an Event-related potential (ERP) waveform. An essential increase in the phase-locking in the alpha (8-12 Hz) and theta bands can occur during a similar epoch as the P1 and the N1 waves that are positive and negative at around 100 ms after stimulus onset; hence the oscillations are most likely to have large effects of P1 and N1 amplitude. The P1 and the N1 components are all linked with early visual recognition, and this likely to be evoked by stimuli that are presented in various sections of the visual field (Townsend, Harris, & Courchesne, 1996). A conspicuous late positive component (LPC) is usually viewed after the appearance of early visual response peaks (Makeig et al., 1999). In the ERP waveform, P300 can be considered to be an LPC. According to (Klimesch, Doppelmayr, Schwaiger, Winkler, & Gruber, 2000), the authors hypothesized that a connection between increased oscillation and that of the P300 ERP component could be seen as a new/old recognition memory task that comprises of words. The authors then identified an increase in theta and delta (1-3 Hz) for words correctly identified as old (the remembered words) at the same time intervals and scalp locations similar to P300.

The findings from the past studies revealed how the brains activity relates with the occurrence of the landmark-based learning in a spatial navigation model. Nonetheless, an in-depth investigation would be required that explores the roles of different temporal processes that are prone to be linked to navigation in the presence of landmarks.

Hence, we decided to explore brain dynamics and neurophysiological activity during spatial navigation. More specifically, we aimed to figure out how navigational-related brain regions are connected and how their interactions and electrical activity vary according to different navigational tasks and environments.

3.3. Materials and Methods

3.3.1. Virtual Environment Designing

Open-source software which is named Maze Suite (version 3.0.4) (Ayaz et al., 2008; Ayaz et al., 2011), is used to create the experiment maze. The Maze Suite designing aimed to help the researchers to build and visualize 3D environments quickly. It composed a complete set of tools that allowing researchers to perform spatial and navigational behavior experiments, motor control tasks and etc., via an interactive and 3D virtual environment. In addition, to design and visualize a 3D environment, the Maze Suite is used for tracking subjects' behavioral performance during an experiment. Maze Suite has been integrated with several technologies/sensors such as EEG, fNIRS, fMRI, and tDCS. In other words, Maze Suits can be used to build and modify a virtual 3D environment, track subjects' behavioral performance through the virtual environment and communicate and synchronize with external devices for physiological and neuroimaging measurement. It consists of three main applications; MazeMaker is used for building and editing the virtual 3D environment by simply drawing on a 2D blank page from a bird's eye view. A mouse click with exact coordination can draw all the walls and floors, and also 3D objects can be imported to the environment, and their properties such as color, texture, position, orientation, and lights are adjustable. MazeWalker is used as a representation framework and the 3D engine for rendering the Maze files. It can monitor and subjects' performance and log events within a trial, send time-markers via a serial port for synchronization, and also open the pre-recorded log file to display the video of the previous activities. The analysis tool of the Maze Suite is named MazeAnalyzer, which can open log files created by MazeWalker to allow researchers to analyze the subjects' behavior such as path, error, time to task completion in the maze. Likewise, MazeAnalyzer can load multiple overlapping paths on the same maze, allowing researchers to compare the actions of different subjects instantly. Log files contain information on the path traveled by a subject as well as where the subject looked at each time and other events occurring with a session.

3.3.1.1. Art gallery structure

Radial Arm Maze (RAM) is one of the well-known tests of spatial memory in rodents. In RAM, the innate propensity of rodents to explore, learn and remember specific spatial positions of food is tested in both spatial memory (place learning) and non-spatial memory (associate learning) (Olton & Samuelson, 1976; Stafstrom, 2006). In recent years, the usefulness of RAM for evaluating the spatial abilities, including working and reference memory in human have been widely investigated. The adaptation of RAM for human studies is facing some limitations because human subjects need much more space than rodents to explore and learn the environment. That is why many researchers developed monitor-based RAM (M-RAM) and head-mounted display-radial arm maze (HMD-RAM) to overcome the limitation regarding the size of RAM and ecological validity related to physical movements, including head/body coordination (Kim et al., 2018).

In this study, the virtual-reality environment, which we name it "Art Gallery", was designed to have the shape of a RAM. The art gallery is composed of a nonagonal central hall in which nine different arms extended outward symmetrically (Figure 20). Symmetry was preserved to prevent ambiguity and to keep the environment as homogenous as possible during the activities. Each arm consists of a lateral enlargement at the end on the left side. We decided to make our art gallery as much as similar to a real art gallery, to do so, we selected some paintings and statues which are located in the main hall and at the end of each arm. Because of the nonagonal shape of the main hall in our maze, we decided to put four statues as landmarks align with the four cardinal directions. Also, six paintings are hanged on the wall of the niches at the end of each arm. The bird view of the position of statues and paintings is shown in Figure 21. We chose to create a blue skybox and to leave the museum open without a ceiling to avoid a narrow and claustrophobic setting. The internal environment of the art gallery is shown in Figure 22.

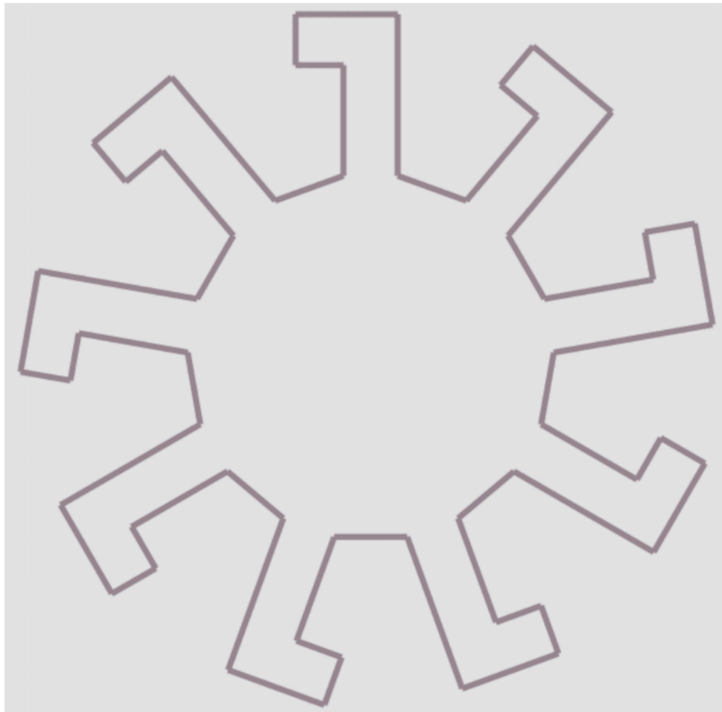


Figure 20. 9-arm radial maze

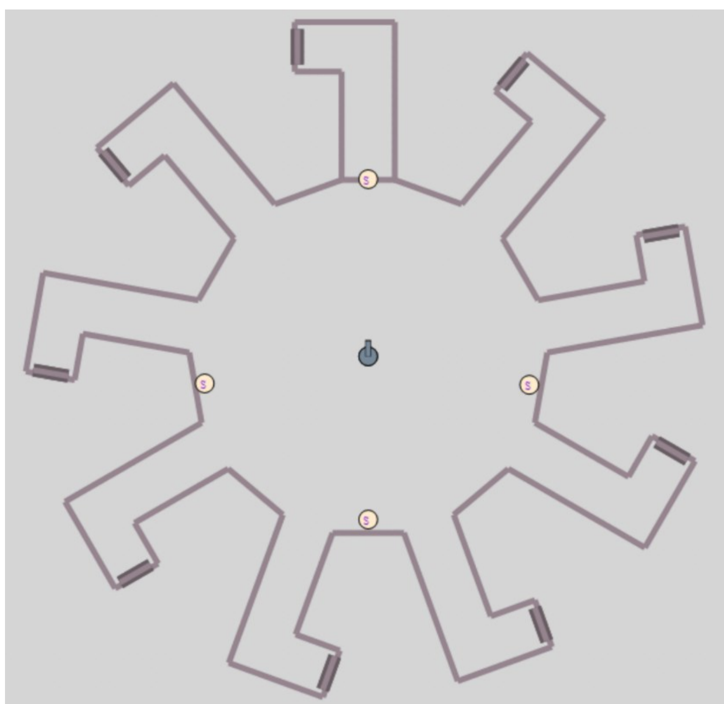


Figure 21. The four statues and their positions are depicted with the white circles and the letter 'S' in the main hall. The positions of the nine paintings are highlighted at the end of the arms.

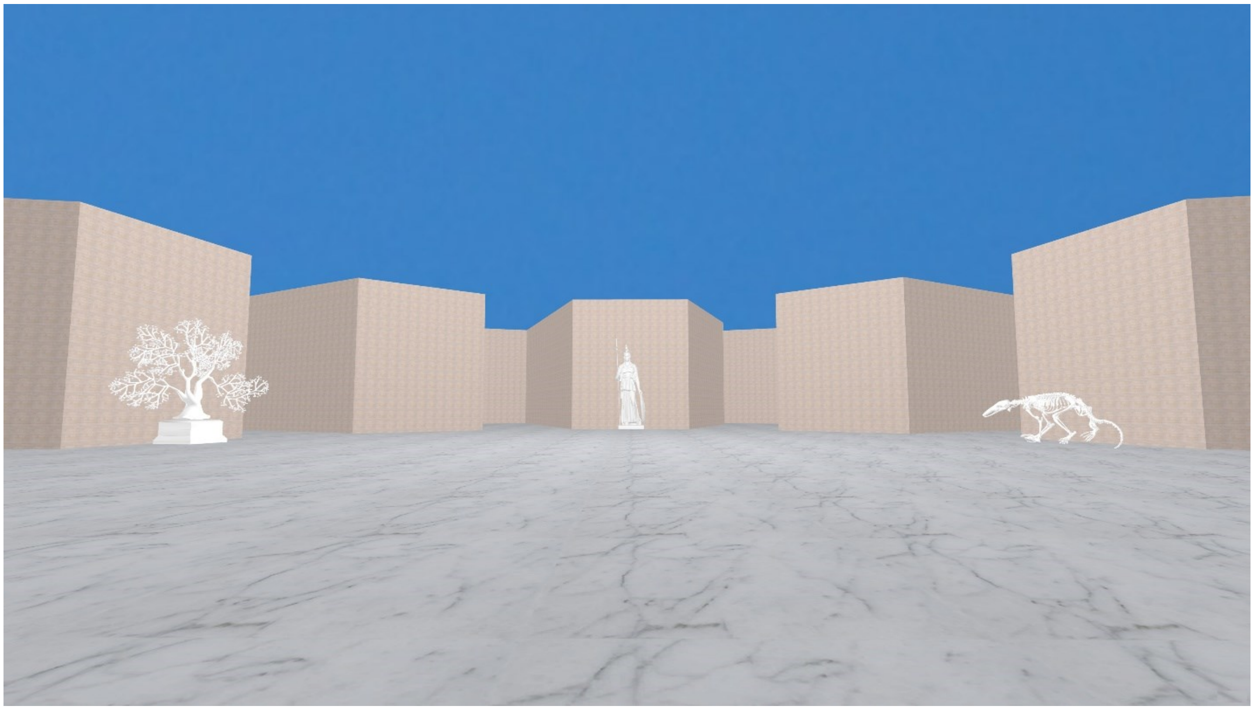


Figure 22. Internal environment of the art gallery

3.3.1.2. Art gallery virtual tour

It is obvious that when subjects were instructed to explore an environment in active mode, all of them will navigate differently, and there will be no control over the time, distance, and behavior of learning. Since this study aims to analyze the brain dynamics during landmark-based learning, we decided to use the passive approach to make all the navigational variables constant across the subjects. Hence, a virtual tour is designed to give all the participants the same opportunity in terms of time, distance, and behavior for vising the art gallery virtually (passive navigation).

As mentioned in the previous section, the MazeWalker can show a video of a previous activity based on a pre-recorded log. Therefore, we created a MATLAB script to make a log file correspond to all activities that each subject needs to learn the environment. For example, looking around, walking in the hall, turn to an arm, walking in the arm, looking at the painting and statues back from the arm. In the virtual tour, the subjects had the opportunity to visit each arm twice at different times to make sure they learned the environment properly.

3.3.2. Subjects

Twenty-one participants participated in the study. Participants were recruited through a Telegram group. All volunteers received a 10 $/h allowance for their participation. Gender distribution was almost kept constant for all conditions. For the analyses, 11 male and ten female participants were included with an average age of 25.42 years (SD = 3.28 years, Min = 20 years, Max = 31 years). All had normal or corrected to normal vision and gave informed consent before the study. The study was approved by the local research ethics committee.

3.3.3. Apparatus

The entire experiment was performed in the Berlin Mobile Brain/Body Laboratory of the Department of Psychology and Ergonomics at Technical University Berlin. The virtual-reality ambiance was presented to our subjects on a computer screen located in one room of the laboratory; the computer was equipped with a keyboard, and subjects were asked to use only two keyboard bottoms which were labeled with "YES" and "No". During the preparation, subjects were always got comfortable on a chair positioned at the same distance in front of the computer screen. The light was maintained switched on so that everyone could both read and listen to the instructions written on an A4-format blank paper sheet. The experiment task was conducted in a desktop-based virtual reality, which requires subjects to sit on a chair in front of a computer screen in a dimly lit room and watch a movie showing a virtual tour through the art gallery.

3.3.4. Procedure

Participants are equipped with 64-channel EEG and seated in a chair in front of a computer screen in a laboratory room. The experiment is composed of a learning phase and a subsequent retrieval phase. During the experimental phases, the subjects and the EEG raw data were monitored via a small camera and a second monitor from the control room. The small camera has streamed the video but does not record the video data of the participants. This could reduce the experimenter's influence on participants' behavior, while the participant could see the possibility to interact with the experimenter when questions arise or help is needed and enables the experimenter to assure smooth progress of the experiment.

The experimental duration of recordings was not exceeded 60 minutes. The overall duration of the experiment was exceeded 90 minutes, including a maximum of 40 minutes of EEG preparations and 50 minutes for learning and test phases. Also, there was be a break after the learning phase of 5 minutes.

3.3.4.1. Landmark-based Learning task

The 3D virtual art gallery tour video in the ground-level first-person view was played for the participants. The art gallery was contained four statues as a landmark in the main hall and nine paintings on the walls of the niches at the end of the arms where they are not visible from the center of the hall. In addition, four golden stars as the target were located at the end of four arms (Figure 23), and the participants' task was to learn the position of these golden stars. Since the visual features of the art gallery, such as sky, color, and texture of the floor, wall height, and bricks, always were the same, hence the subjects were only geared to the landmarks. The learning phase was composed of two rounds, one clockwise exploration, and another counterclockwise exploration, in which the second round continuously was played without any interruption. In this phase, the participants started at the center of the hall while their direction was towards a landmark, which was on the top of one arm. Then they moved toward the arm, and at the end of the arm, they rotated to see both paintings and if a golden star was there. After that, they moved back to the center of the hall and again rotated to face the landmark on the top of the wall. Then they rotated to the next arm, and after moving toward and seeing the end of the next arm backed to the center. Each time after moving back to the center first, they rotated to be faced with the landmark on the top of the wall, then they rotated to the next arm. All these steps were done once clockwise and once counterclockwise for all nine arms, which lasted for 13 minutes.

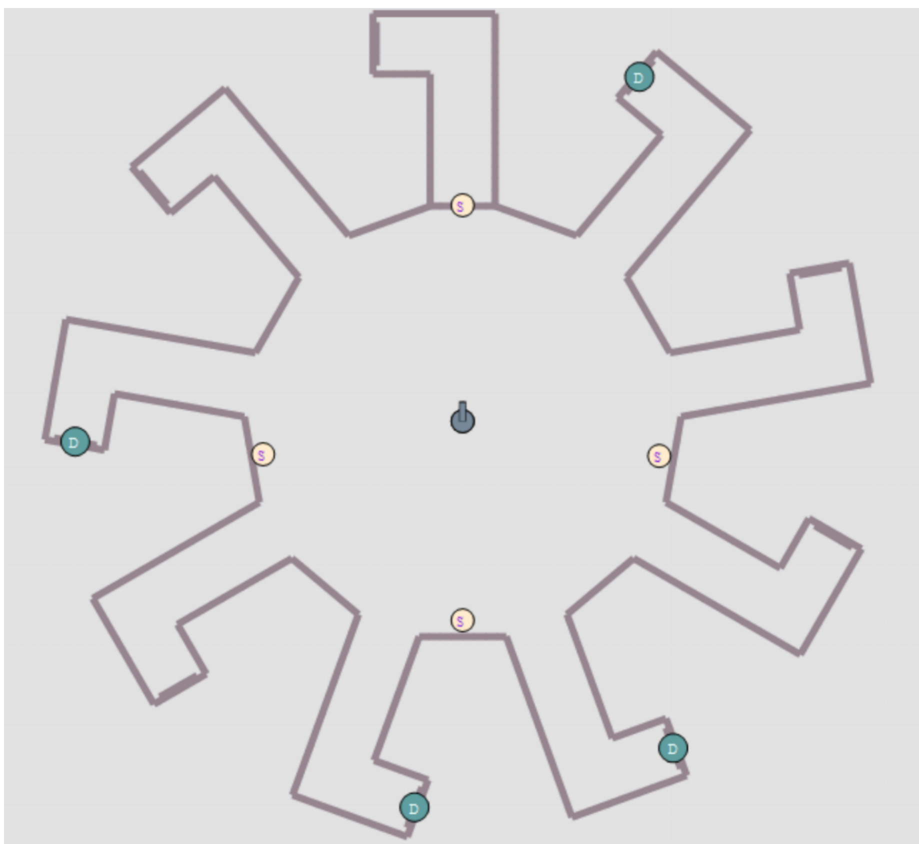


Figure 23. The four stars and their positions are indicated with the green circles and the letter 'D' at the end of four of the nine arms.

It is worthwhile mentioning that the participants were not be informed explicitly that four of nine corridors are rewarded with the golden stars. This was important for keeping their attention high while memorizing the position and arrangement of the landmarks and also their spatial relation with the stars. If they were informed about the exact number of the stars, they might have lost their attention for the rest of the learning phase after finding the fourth star. Specifically, the participants have received the following instruction on the paper:

“The experiment will be started by the instructor. You will have the opportunity to visit an art gallery virtually. The experiment will contain an exploration phase and a test phase. In the exploration phase, you will be conducted through the art gallery, and you will enjoy the artworks. There are several corridors in the art gallery, and at the end of some of them, you will find some golden stars. Your task is to memorize their positions”. Navigating through a virtual art gallery in a ground-level, first-person view is shown to the participants via a movie (Figure 22), and how the golden stars are positioned at the end of the arms is illustrated in Figure 24.

Figure 24. Golden star position at the end of each arm

3.3.4.2. Landmark-based target recognition task

After the landmark-based learning task, a spatial recognition task was performed to test spatial recognition memory. Specifically, recognition of the landmarks that are related to the target and the landmarks that are not related to the target. The spatial recognition phase was comprised of 18 trials where the subjects are asked to retrieve the previously learned information. In each trial, nine snapshots of the nine corridors were presented, and subjects were asked to respond to each corridor snapshot by rating whether the shown corridor leads to a golden star or not (Target vs. Non-Target). For the response, the subjects were instructed to use two keys on the keyboard labeled with "YES" and "NO". In each trial, the first of the shown corridors were chosen randomly, and the snapshots of the other corridors were presented clockwise or counterclockwise. This aim was to induce the feeling of turning on the spot in the center of the art gallery, which is hypothesized to ease spatial information retrieval.

In this phase, all participants have received the following instruction: "In the test phase, several snapshots from the art gallery will be presented, and your task is explained in the following:

a. The stars are located at the same positions as the exploration phase.
b. Each time two snapshots will appear automatically after each other.
c. The first snapshot presents a corridor that contains no artwork, and it needs no action.
d. The second snapshot presents a corridor and artwork. Your task is to respond quickly and as accurately as possible according to the existence of a star at the end of the presented corridor.
e. You can respond with two keys marked with Yes or No on the keyboard in front of you. Please try to avoid making an error.

3.3.5. EEG Recording

The EEG was recorded for both learning, and testing phases using 64 Ag/AgCl electrodes (BrainAmps, Brain Products, Gilching, Germany) positioned in an elastic cap (EASYCAP, Herrsching, Germany) according to the extended 10% system with impedances below 5kΩ. All electrodes were referenced to FCz, and the data was collected with a sampling rate of 500 Hz, band passed from 0.016 Hz to 250 Hz. One electrode below the left eye (vEOG) was used to record vertical eye-movement.

3.3.6. EEG data analysis

The recorded EEG data were analyzed using EEGLAB, an open-source interactive MATLAB toolbox (Delorme & Makeig, 2004) (http://sccn.ucsd.edu/eeglab). The data was filtered using a high-pass filter (1 Hz) followed by a low-pass filter (45 Hz). Subsequently, the filtered data were visually inspected, and noisy channels, dead channels (channel data indicated no activity over longer time periods), muscle activity, mechanical artifacts in the time domain were removed manually, and using EEGLAB "clean_rawdata" plugin. On average, 59.31 EEG channels remained for further analyses (range: 55–63; s = 2.61). Then before re-referencing the data to average, all missing channels were interpolated by spherical algorithm to minimize the potential bias toward a hemisphere. In the next step, Independent Component Analysis (ICA) was computed using the EEGLAB runica function in order to extract independent components (ICs) from scalp electrode signals reflecting maximally statistical independent source time series (Gramann, Ferris, Gwin, & Makeig, 2014; Gramann et al., 2011; Gwin, Gramann, Makeig, & Ferris, 2010). An equivalent dipole model was calculated for all ICs using a Boundary Element Model (BEM) based on the MNI brain (Montreal Neurological Institute, MNI, Montreal, QC, Canada) as implemented by DIPFIT routines (Oostenveld & Oostendorp, 2002; Oostenveld & Praamstra, 2001). Using the ICLabel toolbox, source descriptions were automatically assigned to each, and eye and non-brain components with an assigned probability of higher than 0.8 were selected and eliminated from the data for further processing. Several properties of ICs such as equivalent dipole location, spectra, and residual variance (15%) were used to select the ICs representing brain activity from overall 1186 ICs. Dipoles placed outside of the head model were not further considered. In total, 187 ICs remained for all participants for further analysis with an average of 9.35 ICs per subject (range: 5–15, std = 3.13).

Afterward, epochs were extracted from -200ms to 600ms after the stimulus onset of the landmark pictures in the landmark recognition test. The epochs were baseline corrected using the pre-stimulus period from -200ms until stimulus onset. Only trials with correct responses were accepted. Epochs of one arm type (target, non-target) were aggregated to one dataset resulting in two datasets per subject. The average number of trials for Target and non-Target arms that were correctly answered by subjects were 61.1 (std: 11.69) and 75.15 (std:18.45), respectively. The EEGLAB pre-compute function was used for both scalp-level and source-level analysis to calculate the measure of ERP, power spectrum, event-related spectral perturbations (ERSPs), inter-trial coherence (ITCs), the components' scalp maps, and their equivalent dipole model locations. The power spectrum was computed with Fast Fourier transform (FFT), and frequencies between 3–45 Hz were used for clustering. ERSP and ITC were calculated with 200 time points and 3-cycle wavelets (with a Hanning-tapered window applied).

After precomputation, for the source-based analysis, Principal Component Analysis (PCA) reduced the dimensions of all measures to the first ten principal components, except dipole location with three dimensions. Measures were normalized, weighted, and combined into cluster position vectors. The measures of ERPs and scalp topography were weighted with the standard weighting of 1 (w =1), dipole locations (w = 10), and ERSP (w = 5). Clustering was done by a neural network clustering approach in EEGLAB with the number of clusters set to 15 ICs. The neural network is comprised of 10 hidden layers with the “Random Weight/Bias Rules” training algorithm, and the network performance was evaluated by mean squared error (MSE). The final clustering result was achieved after 1000 epochs, which means all the ICs were fed to the network 1000 times to update the weights of the network.

The dipole location of cluster centroids was estimated based on the Talairach software (Lancaster et al., 2000), providing approximate locations of the cluster centroids. Clusters, including ICs from at least 60% of all participants, were selected, and finally, 4 clusters of interest were identified as brain sources based on the dipole model location of the cluster centroids, and ERSP results are reported for these clusters (Figure 25). No further consideration was given to other clusters reflecting muscle activity or artifacts, as well as to brain clusters without task-relevant power modulations. The centroid of the selected 4 clusters (Table 12) were located in or near right middle occipital cortex (Cl 2; x=33, y= -63, z= 13; 18 ICs, 16 participants), left posterior cingulate cortex (Cls 8; x=-26, y= -66, z= 16; 14 ICs, 13 participants), paracentral lobule (Cls 10; x=2, y= -30, z= 45; 17 ICs, 14 participants), precuneus (Cls 13; x=0, y= -73, z= 26; 17 ICs, 13 participants).

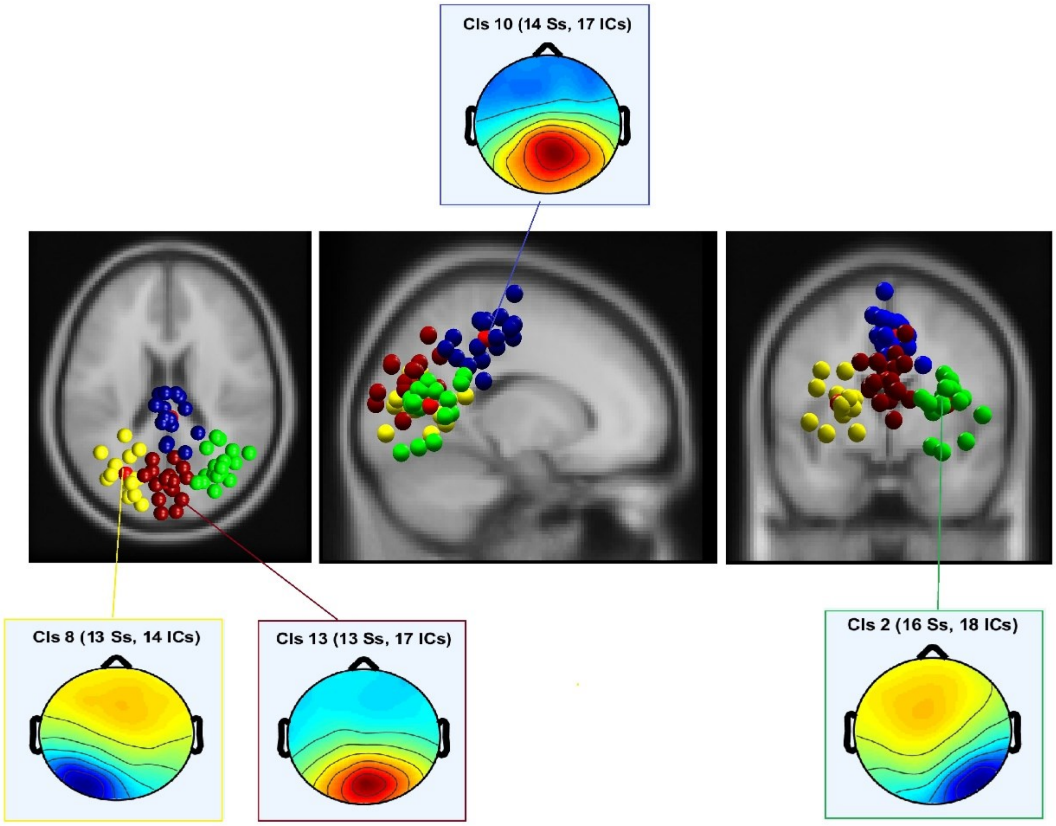


Figure 25. Dipole locations of independent component clusters and respective mean scalp maps. The middle row displays equivalent dipole models of each independent component (with small spheres) and the centroids of each component cluster (red spheres) projected onto the standard brain. The average scalp map of each cluster is displayed and color-coded, corresponding to the color-coding used for the dipoles models. For each cluster, the number of participants and the number of ICs are given. Cluster centroids are located in or near the right middle temporal gyrus (Cls 2), left posterior cingulate cortex (left PCC) (Cls 8), paracentral lobule (Cls 10), Precuneus (Cls 13).

Table 12. Centroid of selected clusters and the brain regions

	X	Y	Z	Brain Region
Cl 2	33	-63	13	Right middle temporal gyrus
Cl 8	-26	-66	16	Left posterior cingulate cortex (left PCC)
Cl 10	2	-30	45	Paracentral lobule
Cl 13	0	-73	26	Precuneus

3.4. Results

3.4.1. Behavioral analysis

In the test phase, to evaluate the overall behavioral performance of the subjects to respond to the Target arm and Non-Target arm correctly, we considered the correct responses to Target and non-Target arms as true positive (TP) and true negative (TN), respectively. Accordingly, the incorrect responses to the Target and Non-Target arms were considered as false positive (FP) and false-negative (FN), respectively. In the next step, we calculated the accuracy, sensitivity, specificity, and false-positive rate for all subjects by the following formulas:

$$Accuracy\ (\%) = \frac{TP + TN}{TP + TN + FP + FN} \times 100$$

$$Sensitivity\ (\%) = \frac{TP}{TP + FN} \times 100$$

$$Specificty\ (\%) = \frac{TN}{TN + FP} \times 100$$

$$False\ positive\ rate = \frac{FP}{FP + TN} \times 100$$

The above-mentioned metrics were calculated for each subject, and after averaging across all subjects, the results showed that subjects with an average accuracy of 87.95% responded to the Target and Non-Target arms. The average sensitivity and specificity for responding to the Target and Non-Target arms were 87.17% and 89.32%, respectively. In addition, the average false positive rate was 10.67%. Further, the error rate of both Target and Non-Target conditions for all subjects is calculated and indicated no significant difference ($p<.64$) and is shown in Figure 26.

Moreover, all correct responses were considered for calculating and comparing the reaction time (RT) between two conditions of Target and Non-Target arms. The obtained average RT indicated that subjects responded to correct Target arms (mean 1196.53ms, median 976ms) significantly faster than responding to Non-Target arms (mean 1322.27ms, median 1010ms) (Welch's t-test, $p<0.001$) (Figure 27).

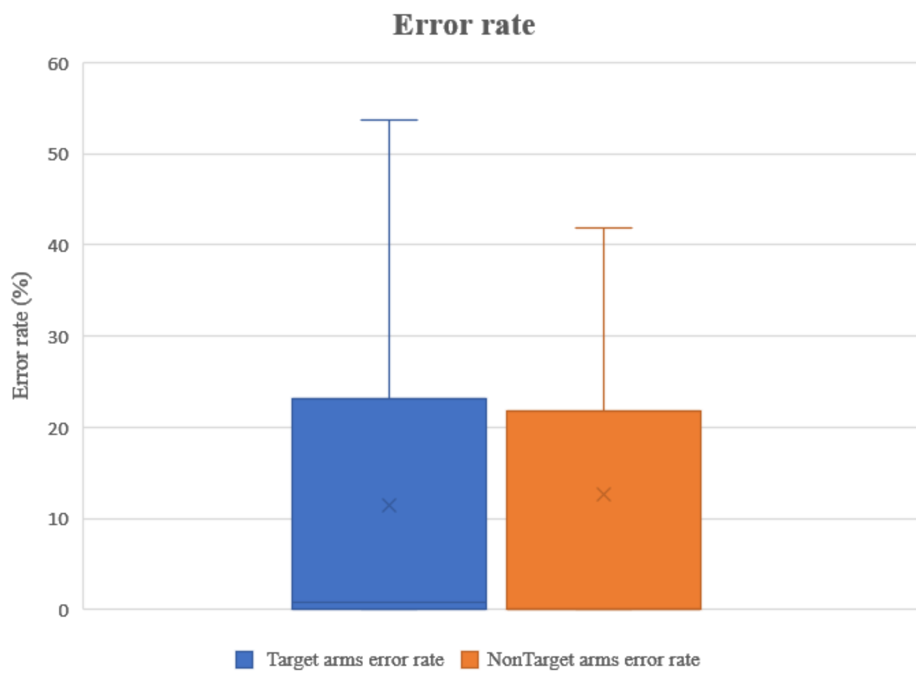


Figure 26. Error rate for responding to Target and Non-Target arms

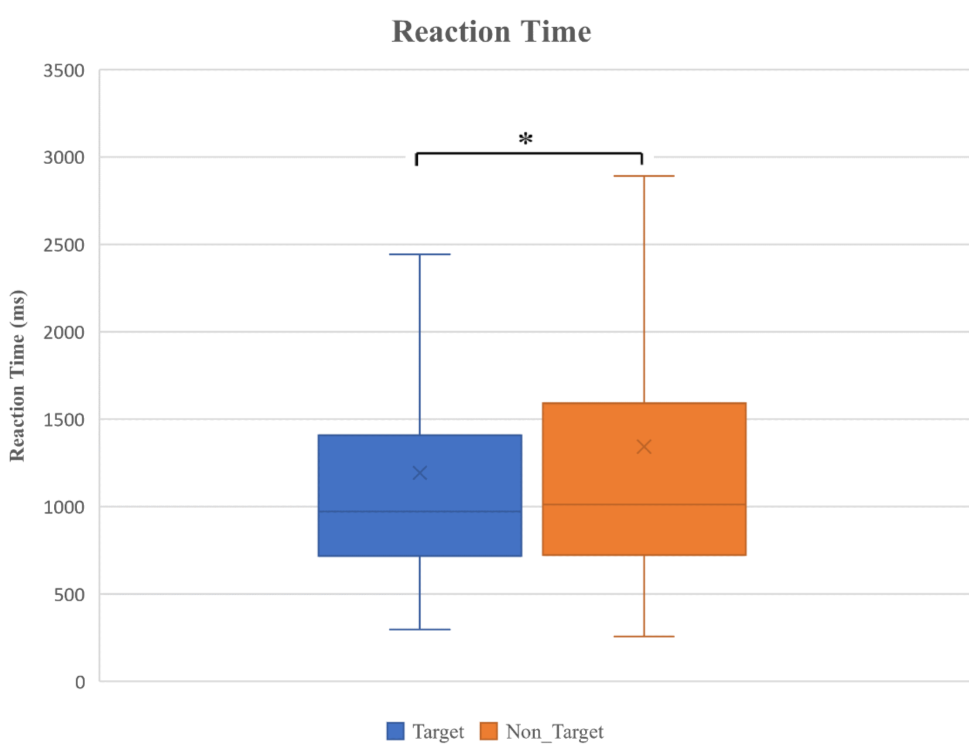
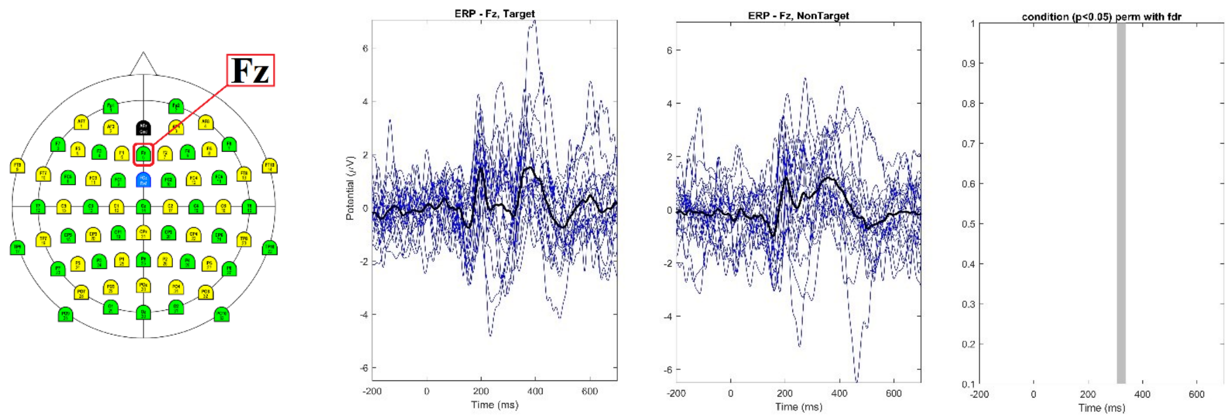


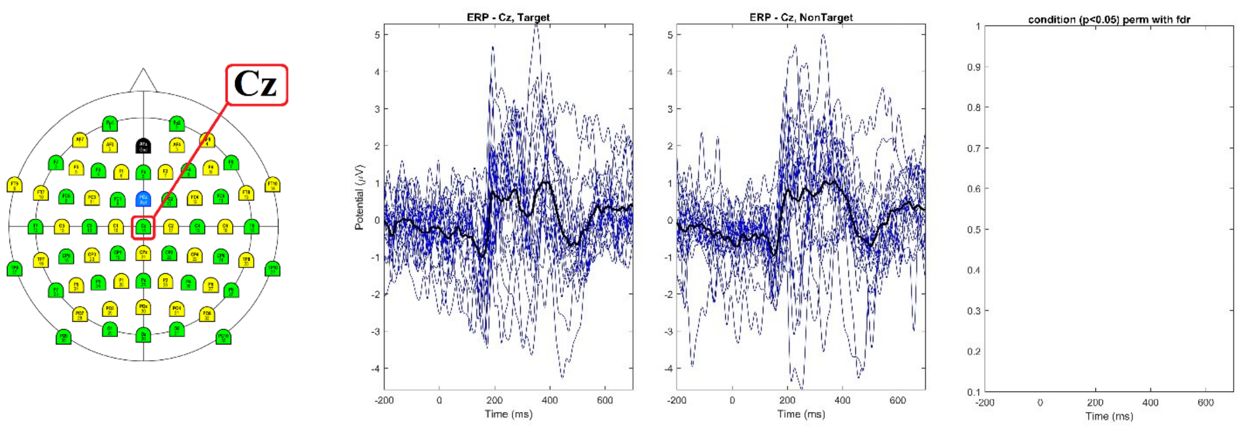
Figure 27. Reaction time for response to Target and Non-Target arms

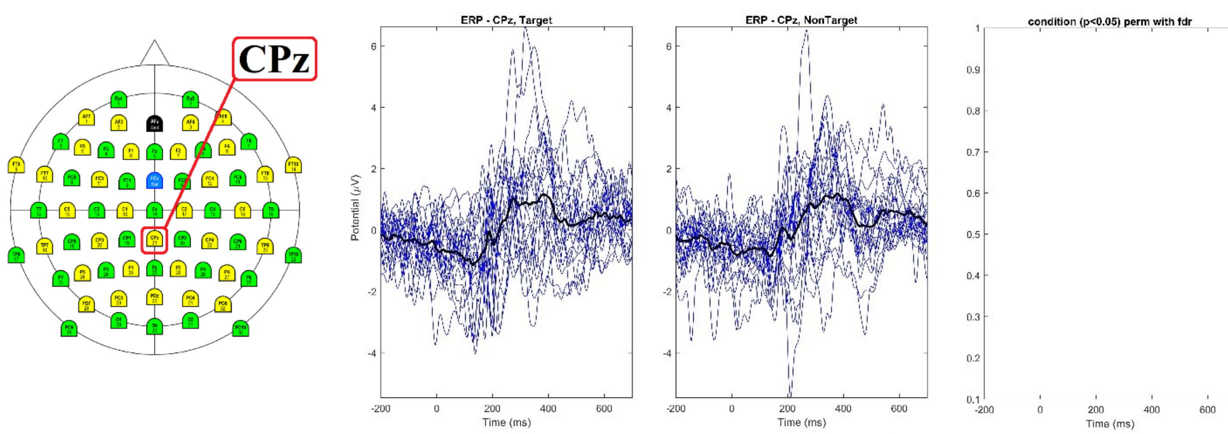
3.4.2. Electrode-level analysis

An overview of the ERPs with the onset of landmark presentation is shown in Figure 28 for six representative channels of the 64-channel montage for Target and Non-Target conditions. The solid lines in Figure 28 show the grand average of ERPs of these two conditions. Although there was a significant difference between Target and Non-Target conditions over frontal, occipital, and partial occipital recording sites, no such difference was presented for central, central parietal, and parietal regions. Furthermore, the grand average of two conditions with standard error is shown in Figure 29. The results showed that the N200 amplitude of Fz for Target condition (mean = -0.10 μV, SD = 0.29) was statistically significantly negatively higher than Non-Target condition (mean = 0.84 μV, SD = 0.17) (Z = -5.40, p< .001) while no significant differences neither for P300 nor N200 were shown for the Cz (Z = -1.15, p< .24604) and CPz (Z = -0.07, p<.94). In addition, Oz revealed significantly larger average P300 amplitude for Target arms (mean = 2.58 μV, SD = 0.04) compared with Non-Target (mean = 1.24 μV, SD = 0.66) (Z = 5.92, p<.001). Similarly, Pz, indicated significantly higher late positive component (LPC) amplitude for Target condition (mean = 1.82 μV, SD = 0.22) than Non-Target condition (mean = 1.12 μV, SD = 0.08) (Z = 6.97, P<0.001). POz was another electrode with a mean P300 amplitude of 3.33 μV (SD = 0.27) for the Target condition showed a significant difference compared with the Non-Target condition with the mean of 1.65 μV (SD = 0.38) (Z = 5.39, p<0.001).

Electrodes	Target Condition	Non-Target Condition	P-value < 0.05







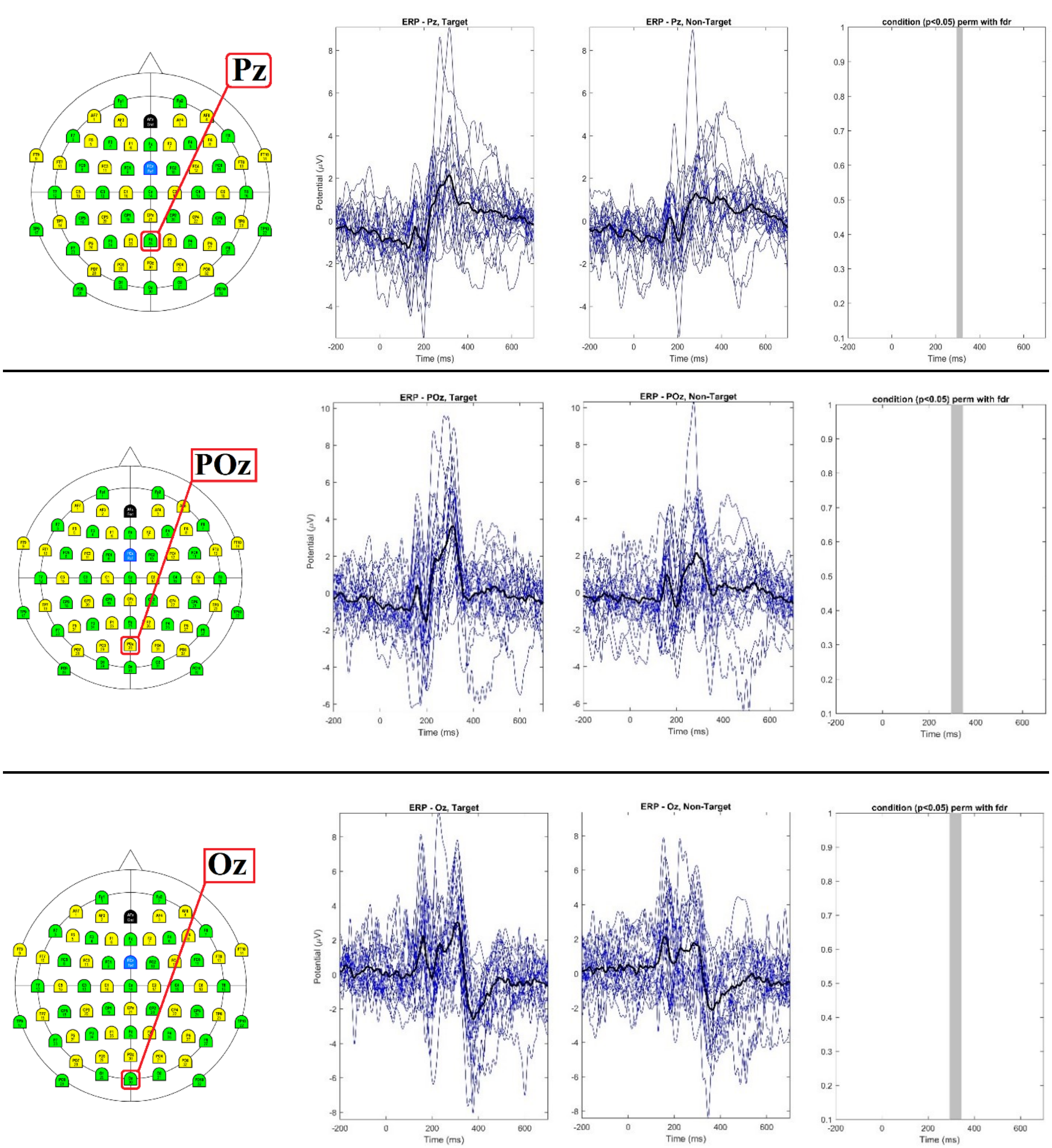
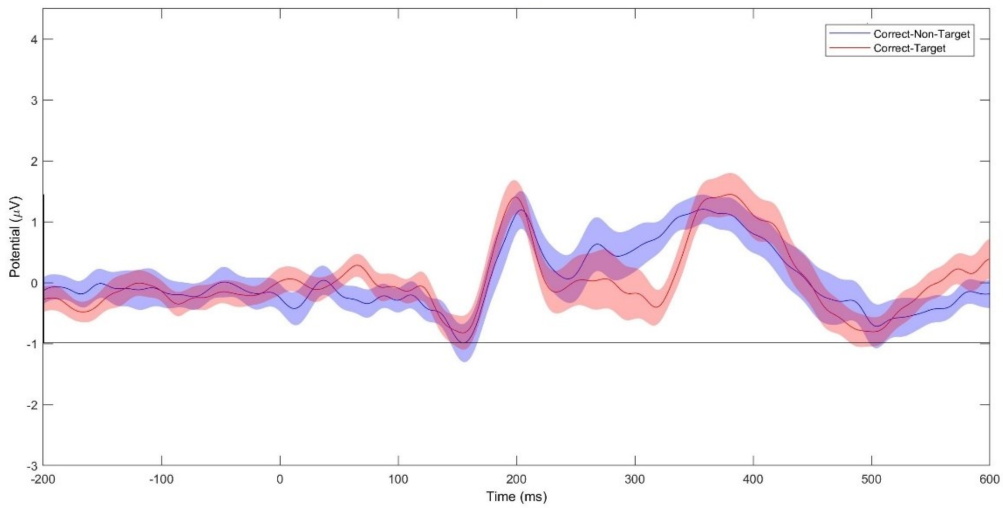


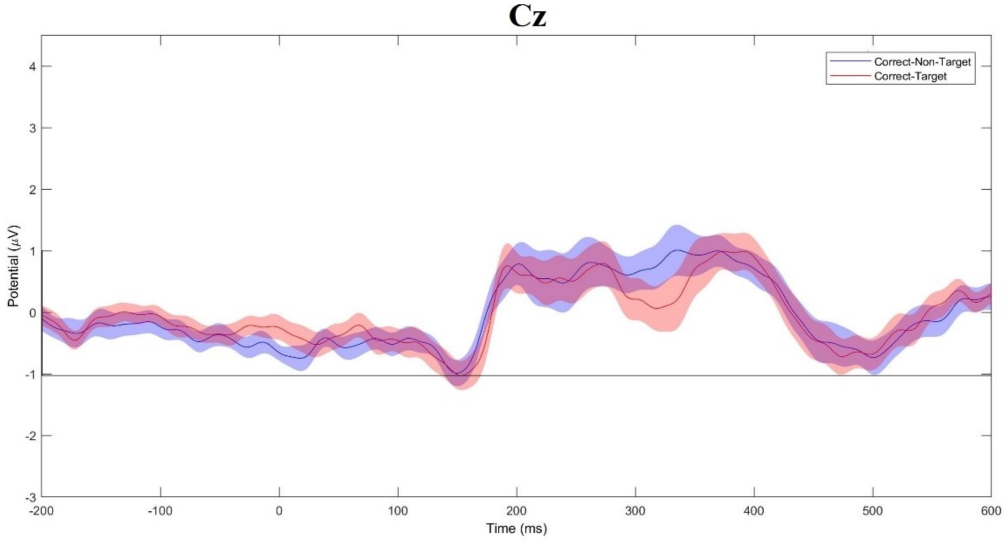
Figure 28. Grand average ERPs on midline electrodes (Fz, Cz, CPz, Pz, POz, and Oz). **Left column:** Corresponding electrode was marked as red. **Two middle columns:** Grand average of ERPs (solid line) for Target and Non-Target conditions. **Right column:** Significant difference between two conditions ($p<0.05$) with FDR correction.

Fz



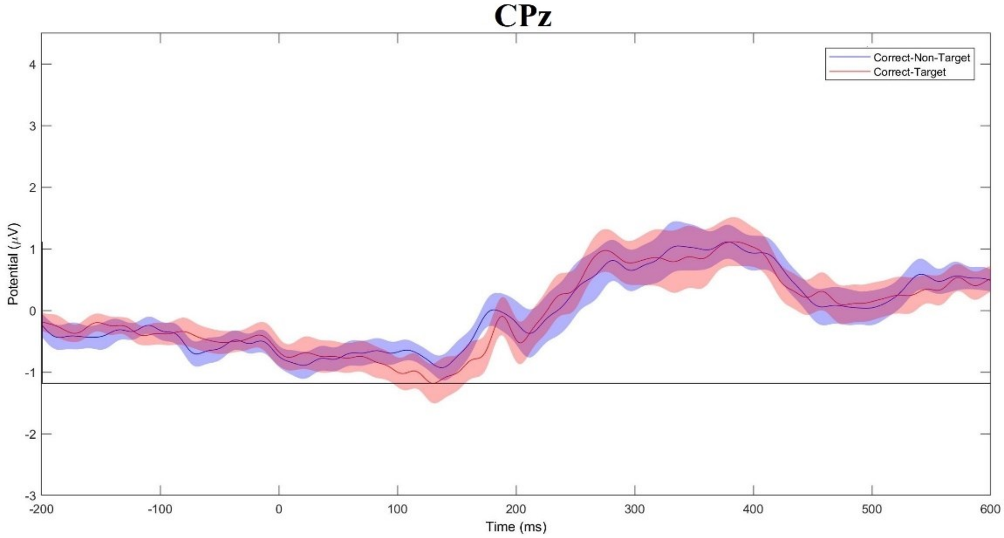
Correct-Non-Target
Correct-Target
Potential (μV)
Time (ms)

Cz



Correct-Non-Target
Correct-Target
Potential (μV)
Time (ms)

CPz



Correct-Non-Target
Correct-Target
Potential (μV)
Time (ms)

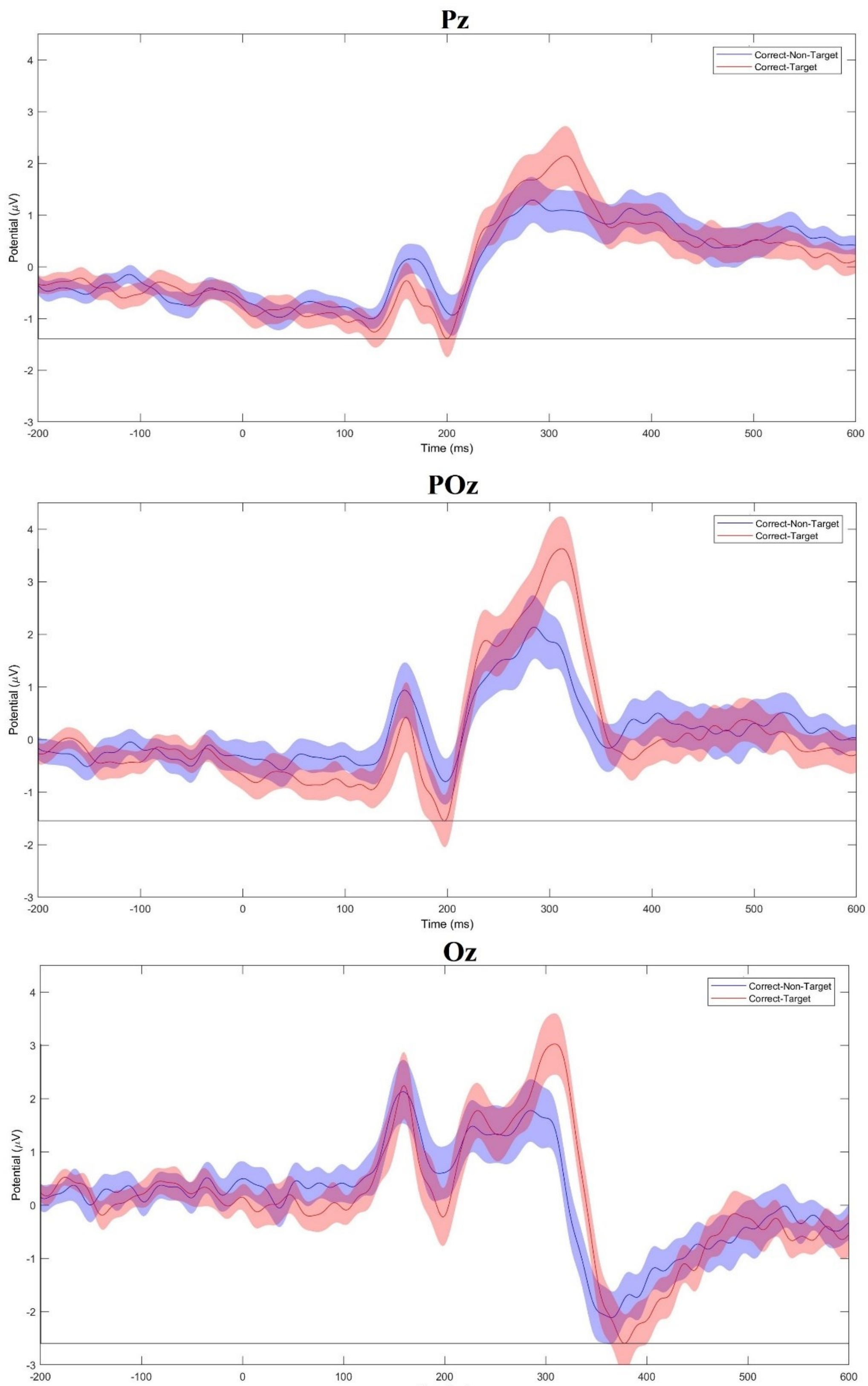


Figure 29. Grand average ERPs on midline electrodes (Fz, Cz, CPz, Pz, POz, and Oz) with standard error for Target and Non-Target conditions.

3.4.3. Source-level analysis

Figure 30 illustrated the chosen clusters showing equivalent dipole locations projected onto the Montreal Neurological Institute (MNI) brain with the corresponding scalp map for each cluster. Mean ESRP images of each cluster for each condition (Target and Non-Target) and the significant spectral power difference ($p<0.05$) between two conditions are shown in Figure 25. It is worth noting that the significance level was corrected using the false discovery rate (FDR) approach (Benjamini & Hochberg, 1995).

The ERSP results of three clusters (Cl8, Cl10, and Cl13) indicated a significant difference between Target and Non-Target at various frequencies. Significant difference between these two conditions were observed in or near left posterior cingulate cortex (Cls 8; x=-26, y= -66, z= 16; Brodmann area (BA) 19), in or near paracentral lobule in right hemisphere (Cls 10; x=2, y= -30, z= 45; BA 31), and precuneus in left hemisphere (Cls 13; x=0, y= -73, z= 26; BA 31). The left posterior cingulate cortex (left PCC) (Cls 8) revealed theta band modulation for both conditions of Target and Non-Target from around 4 Hz to 8 Hz in the time widow from 150ms to 400ms after stimulus onset given that the Target condition exhibited significantly stronger theta (4-7Hz) activity compared to Non-Target condition. In addition, an increase in theta band was accompanied by a decrease in alpha (11-13Hz) and beta band (13-30Hz) for the time period from 200ms to 300ms post-stimulus. In addition, the left PCC indicated strong desynchronization in alpha (9-13Hz) and beta (13-26Hz) bands from 400ms to 600ms post-stimulus for both conditions. The significant difference ($p<0.05$) between Target and Non-Target conditions in left PCC is revealed in the theta band (4-8Hz) from 200ms to 300ms after stimulus onset. Spectral perturbation in or near the right paracentral lobule (Cls 10) showed an increase in theta band between 3 Hz and 8 Hz from 100ms after stimulus onset up to 600ms with a stronger theta activity from the time period of 150ms to 300ms for Target condition and 150ms to 400ms for Non-Target condition. Similar to the left PCC, the right paracentral lobule also indicated desynchronization in the alpha band (8-13Hz) and beta band between 13Hz and 26Hz from 300ms to 600ms post-stimulus. The comparison of ERSP between two conditions indicated a significant difference ($p<0.05$) from 3Hz to 4Hz approximately 50ms after stimulus onset to 200ms post-stimulus. The precuneus (Cls 13) revealed prominent spectral perturbation in theta band from 3Hz to 8Hz for both Target and Non-Target conditions from 100ms to 400ms post-stimulus. More specifically, the precuneus showed a strong power increase in theta band from 200ms to 400ms post-stimulus with a center on 300ms. Further, the Target condition indicated a strong alpha (8-13Hz) power increase for the time period 200- 400ms post-stimulus. The alpha (9-13Hz) and beta (13-26Hz) band were suppressed for both Target and Non-Target conditions from 400ms up to 600ms post-stimulus. The significant difference ($p<0.05$) between two conditions was revealed in the theta band from 6Hz to 8Hz and alpha band (8-13Hz).

In addition to the above-mentioned clusters that the Target and Non-Target conditions were significantly different in some frequencies, the is another cluster revealed prominent spectral perturbation in the theta band. The strong power increase in or near right middle temporal gyrus (Cl 2; x=33, y= -63, z= 13, BA19) was revealed for both Target and Non-Target conditions for theta (4-8Hz) band from 100ms to 300ms post-stimulus (Figure 25). The increase in theta band was accompanied by a decrease in beta band 13-26Hz and 13-30Hz for Target and Non-Target conditions, respectively, between 200ms and 300ms post-stimulus. Moreover, both conditions indicated stronger alpha (8-13Hz) and beta (13-26Hz) bands desynchronization from 400ms up to 600ms post-stimulus onset. However, no significant differences were observed between the two conditions.

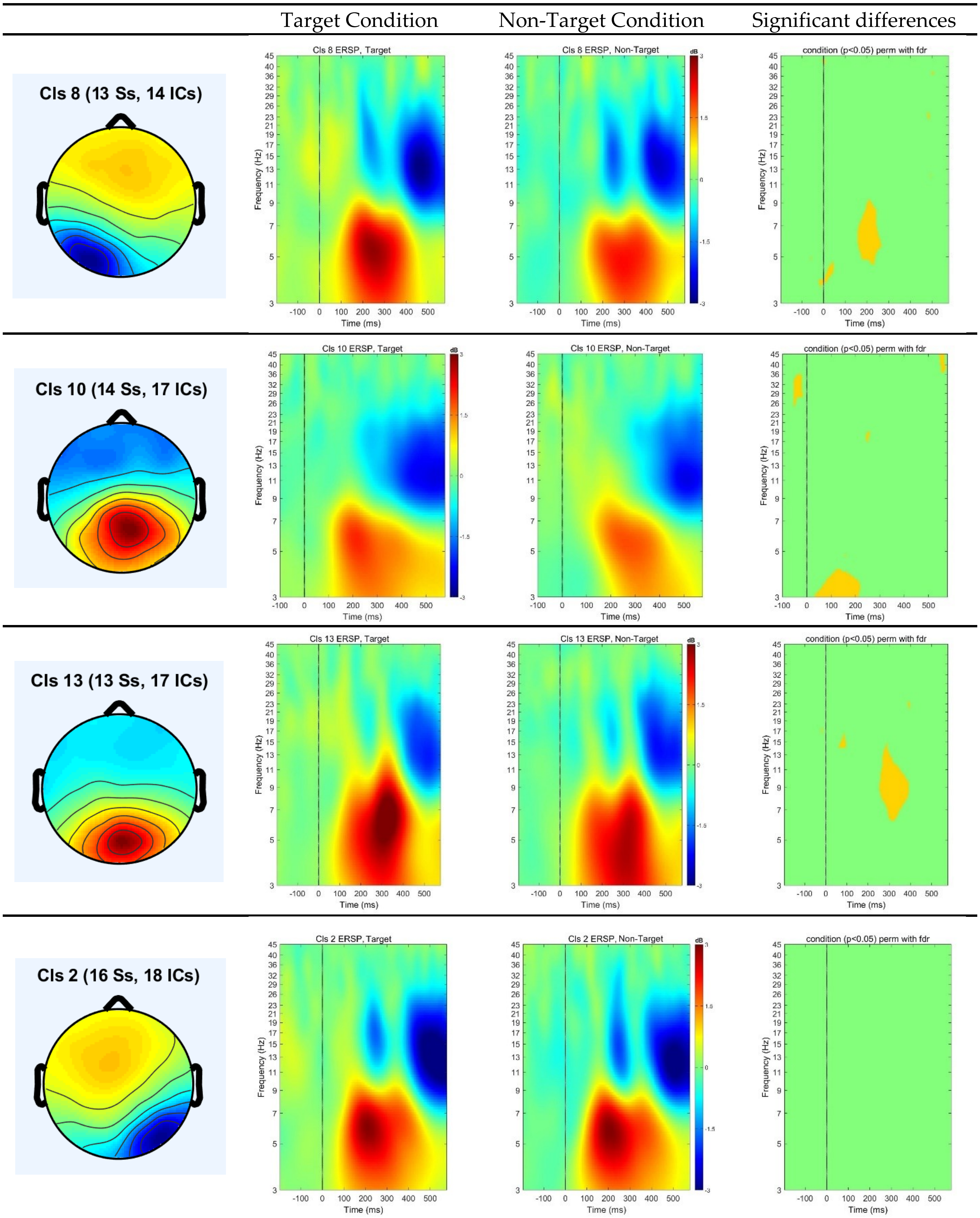


Figure 30. Event-related spectral perturbation (ERSP) results for the Target and Non-Target condition and the significant differences with p<0.05 with FDT correction. The Y-axis shows frequency (Hz) from 3 Hz to 45 Hz, and the X-axis shows time (ms) from -200 ms to 600 ms. Significant results were displayed for ERSPs

in or near the left posterior cingulate cortex (Cls 8), the paracentral lobule (Cls 10), and the precuneus (Cls 13).

3.5. Discussion

Previous electrophysiological and neuroimaging studies suggested that medial temporal, frontal, and parietal brain regions work together to give humans the ability for route-following, construction of new routes, plan and make decisions, and incorporation of sensorimotor knowledge for egocentric-based and allocentric-based navigation (Bischof & Boulanger, 2003; Caplan et al., 2001; Caplan et al., 2003; Galati et al., 2000; Kahana et al., 1999; Lin et al., 2015). Quite recently, the brain oscillation during human spatial navigation has investigated, focusing on sensorimotor integration and spatial learning (Caplan et al., 2003; Ekstrom et al., 2005; White et al., 2012). The current study investigated brain dynamics related to landmark-based learning during spatial navigation. Since there are a few studies that used EEG to investigate brain functions during spatial navigation, specifically landmark-based wayfinding, this study aimed to provide a precise description of encoding and retrieval of information during landmark-based learning to bridge the gap with the previous human spatial navigation studies.

The participants passively navigated through a 9-arm radial maze designed to look like an art gallery. There were some landmarks in the main hall of the art gallery, and some golden starts at the end of some arms as a target, and participants were asked to memorize the targets' position. After learning the targets' position, in the test phase, several snapshots were showed to the participants; each snapshot was composed of a baseline (an arm with no landmark) and the main stimuli, which included an arm and a landmark. The subjects needed to respond to the presented arm was Target or Non-Target with respect to the landmark showed within the main stimuli snapshot.

The behavioral performance indicated that the participants learned the experiment very well with respect to the low false-positive rate (FPR= 10.67%), which FP here was defined as the Target arms selected not correctly. More precisely, we calculated the error rate of both Target and Non-Target conditions separately to find out to what extend they learned the task and whether there will be any difference in the accuracy between selecting an arm as a Target or Non-Target. The results indicated that there was no significant difference between the error rate of these two conditions, which indicated the accuracy and the quality of perceptual representation for both conditions were almost the same. The comparison between the reaction time (RT) of subjects to respond to the Target and Non-Target arms revealed that the RT to the Target arm was significantly faster than Non-Target arms. Given that the RT physiologically is a complex phenomenon (Kuang, 2017; Reigal Garrido et al., 2019) and cognitive processes like attention as an internal factor would be a variable involved in the RT manifested by a person(Giuliano, Karns, Neville, & Hillyard, 2014; Gomez-Ramirez, Hysaj, & Niebur, 2016; Jehu, Desponts, Paquet, & Lajoie, 2015; Prinzmetal, McCool, & Park, 2005; Vaportzis, Georgiou-Karistianis, & Stout, 2013). The possible reasons for the faster reaction time in Target conditions than Non-Target conditions with no effect of the accuracy might be because of the subjects' involuntary attention to Target arms more than Non-Target arms (Eimer, Nattkemper, Schröger, & Prinz, 1996). As already reported by (Prinzmetal et al., 2005) that involuntary attention affects reaction time but not accuracy.

As a matter of fact, human behavior is systematically related to brain activity. Many researchers reported that the N200 (N2) and P300 (P3) are closely associated with the cognitive processes, selective attention, and conscious discrimination (Kok, 2001; McCarthy & Donchin, 1981; Patel & Azzam, 2005; Polich, 2007; Sutton, Braren, Zubin, & John, 1965). Typically, the N2 is evoked before the motor response, indicating its connection to the cognitive processes of stimulus recognition, discrimination, and categorization, and its peak latency has been shown to be consistent with measures of executive function and attention (Hoffman, 1990). In the current study, frontal area (Fz) revealed a significantly higher N2, specifically N2c (one of the N2 sub-components) amplitude for Target condition than Non-Target. The N2c typically appears during the classification tasks in frontal and central areas (Pritchard, Shappell, & Brandt, 1991). Since the N2 is linked with attention and N2c is more related to the classification, we can conclude that subjects paid more attention to recognize and classify the Target arms from Non-Target arms.

Moreover, in this experiment, the N2 (around 320 ms) occurred later than a typical N2, and it could be because of the difficulty in Target-arm stimulus classification similar to the previous finding of (Berti, Geissler, Lachmann, & Mecklinger, 2000) that observed a similar complex at N350. We also speculated that the higher N2 amplitude for Target condition might be related to the faster reaction time of the subjects for responding to the Target arms than Non-Target arms. Our findings replicated the result of a previous study (Bahramali, Gordon, Li, Rennie, & Wright, 1998) that they found significantly larger N2 amplitudes in faster RT compared with slower across frontal to parietal regions (midline electrodes (Fz, Cz, Pz)). Furthermore, from the behavioral analysis, we concluded that the subjects' attention to respond to the Target arms was more than Non-Target arms. Since the N2 component is attentional basis, a statement that can be related to the higher N2 amplitude of the frontal area in our experiment is the subjects paid more attention to the Target arms than Non-Target arms. The same finding was reported by (Pardo, Fox, & Raichle, 1991; Polich, 2007; Posner, 1992; Posner & Petersen, 1990), from the oddball paradigm that frontal lobe activity in discriminating between target and standard stimuli is sensitive to attentional demand induced by task performance.

The other significant difference between Target and Non-Target conditions was revealed in parietal area (Pz). The results showed a significantly higher amplitude of late positive component (LPC) for Target than Non-Target arm. LPC is one of the ERP components which is usually visible in the same time window as the P300 and mostly studied in explicit recognition memory (Friedman & Johnson Jr, 2000; Münte, Urbach, Düzel, & Kutas, 2000). The increase of LPC amplitude is associated with an increasing amount of information that is relocated (Vilberg, Moosavi, & Rugg, 2006; Wilding, 2000; Wunderlich & Gramann, 2018). Hence, we considered the amplitude of the LPC at parietal electrode as an indicator of the recollection process of recognition memory (Friedman & Johnson Jr, 2000; Wunderlich & Gramann, 2018). The significantly larger amplitude of LPC observed for Target arms might represent an increased amount of retrieved information for recognition of the Target arm than Non-Target arms. We argue that subjects were processed the target arms more elaborate to recognize them from Non-Target arms, and consequently, more information was recollected from memory as represented in the amplitude of the LPC.

Furthermore, the parieto-occipital area (POz and Oz EEG site), including the posterior parietal cortex (PPC), showed a significant difference between Target and Non-Target conditions. The P300 amplitude related to Target arms was significantly greater than Non-Target arms. The PPC plays a crucial role in spatial representation, and damage in PPC can cause various types of spatial disorientation in patients (Husain & Nachev, 2007; Kolb & Whishaw, 2003). In addition to the sense of orientation, PPC is essential for generating and guiding spatial awareness, limb locomotion and how their statuses co-vary during movement, and is mainly responsible for the automatic detection and encoding of the location of salient stimuli (Constantinidis & Steinmetz, 2005; Whitlock, 2017). However, we believe the reason for more amplitude of P300 for Target arms could be because of the direct attention of subjects to targets arms than the Non-Target arms. This is aligned with the findings of (Bledowski et al., 2004) and (Corbetta & Shulman, 2002) that more activity in PPC is related to the role of this region in goal-directed attention and visuomotor integration.

In recent years, several researchers have been investigated the role of theta oscillation and its increase during different human spatial navigation-related tasks in virtual environment (Araújo et al., 2002; Bischof & Boulanger, 2003; Caplan et al., 2003; Cornwell et al., 2008; Ekstrom et al., 2005; Kahana et al., 1999; D. J. Mitchell, McNaughton, Flanagan, & Kirk, 2008). The increase in theta power is correlated with a variety of memory paradigms such as episodic, spatial, or semantic tasks (Bastiaansen & Hagoort, 2003), and more specifically, theta oscillation has been associated with the encoding and retrieval of spatial information (Herweg & Kahana, 2018). Allocentric representations have primarily associated with the medial temporal lobe (MTL), which code specific spatial locations to form the basis for a cognitive map (Ekstrom, Arnold, & Iaria, 2014; Herweg & Kahana, 2018; Edward C Tolman, 1948) and the information can be decoded and retrieved whenever the spatial relations of objects or landmarks are needed. In the present study, a cluster in or near the right middle temporal gyrus revealed a very strong theta power for both Target-arms and Non-Target arms between around 150-200 ms post-stimulus, which indicates the role of theta wave during the encoding and retrieval of spatial information for Target and Non-Target arms, however, there was no significant difference between these two conditions. In contrast with the MTL, a cluster in or near the left PCC showed significantly stronger theta power for Target-arms than Non-Target arms around 200 ms post-stimulus. Several studies revealed that PCC, by receiving the major inputs from parietal cortical areas (from the somatosensory and dorsal visual stream) play a pivotal role in spatial processing, action in space, and some kinds of memory, specifically episodic memory retrieval (Nielsen, Balslev, & Hansen, 2005; Rolls, 2019; Rolls & Wirth, 2018; B. Vogt, 2009; B. A. Vogt & Pandya, 1987). It is also hypothesized that dorsal and ventral subregions of PCC are functionally different so that the ventral positions were more likely to be activated by spatial encoding, i.e., passive viewing of scenes or active navigation without a demand to respond, perform a spatial computation, or localize oneself in the environment while dorsal portions were more likely to be activated by cognitive demands to recall spatial information or to produce judgments of distance or direction to non-visible locations or landmarks (Burles, Umiltá, McFarlane, Potocki, & Iaria, 2018). The theta oscillation in PCC seems to be phase-locked with the hippocampus theta frequency (Colom, Christie, & Bland, 1988; Leung & Borst, 1987), and it can be related to short- and long-term memory processes (Bastiaansen & Hagoort, 2003; Kaplan et al., 2014; Raghavachari et al., 2001). So, we can conclude that the significantly higher power of theta band for Target-arms could be because of the more memory load related to the retrieval of spatial information of the targets at the end of some arms.

The Paracentral lobule is another brain area that indicated a significantly higher theta power for Target arms than Non-Target arms. Paracentral lobule, which is also named primary motor cortex, is responsible for executing voluntary movements. The higher power of theta oscillation could be because of the faster reaction time of subjects for responding to Target arms than Non-Target arms.

Besides the paracentral lobule, the precuneus demonstrated significantly strong power modulation in the theta and alpha frequency bands for Target arms than Non-Target arms. The precuneus is integrated with a wide variety of tasks such as episodic memory retrieval, visuospatial imagery, and self-processing operations, namely first-person perspective-taking and experience of agency (Cavanna & Trimble, 2006; Lundstrom, Ingvar, & Petersson, 2005; Suchan et al., 2002; Vogeley et al., 2004). In recent years, several studies have been investigated the allocentric spatial memory tasks in virtual environment, and they confirmed that some brain regions such as medial temporal lobe, lateral and medial PCC implicated in allocentric spatial memory (Aguirre & D'Esposito, 1997; Bohbot, Iaria, & Petrides, 2004; Jordan, Schadow, Wuestenberg, Heinze, & Jäncke, 2004; Parslow et al., 2004). More specifically (Frings et al., 2006) investigated the rule of precuneus in allocentric spatial location encoding and recognition in a virtual environment. Subjects were instructed to memorize different locations of an object during encoding, and they had to recognize previously learned object locations. The result of their study revealed that precuneus bilaterally was activated during both encoding and retrieval of spatial location of object. Similarly, in our experiment, the precuneus showed prominent spectral perturbations in the theta band for both Target and Non-Target arms. However, the theta power of the Target arms was significantly higher than Non-Target arms, and also, it was accompanied by a power increase in the alpha band. It is worth mentioning that alpha oscillation is related to several cognitive domains such as attention, perception, sensory, motor, and memory functions (working memory and long-term memory) (Adrian & Matthews, 1934; Lehmann & König, 1997). The synchronization of alpha oscillation for both Target and Non-Target arms in precuneus might reflect the decrease in spatial attention after gathering sufficient visual information (Delaux et al., 2021), and inhibition of task-irrelevant memory entries and a significantly higher power of alpha for Target arms could be because of prolonged selective access attempts to long-term memories (Klimesch, 2012; Penfield & Jasper, 1954).

3.5. Conclusion

The findings from previous studies form the foundation for this dissertation. We examined how electrical activity in the brain correlates with the occurrence of landmark-based learning in a spatial navigation paradigm. We investigated both scalp-level and source-level analysis approaches to have a better understanding of brain dynamics during landmark-based spatial navigation. In conclusion, the findings of the current research indicate that different human brain regions are involved in spatial navigation. Several cognitive processes, such as visual perception, attention, spatial orientation, memory, encoding, and retrieval of information during learning and recognition, etc., are contributing to successful and accurate spatial navigation. Our findings regarding the theta wave support the general trend in brain oscillation during human spatial navigation, as stated in previous EEG and iEEG studies. Most importantly, this study showed the EEG-based experiment's capability for time-frequency analysis of the brain dynamics during spatial navigation with high temporal and proper spatial resolution.

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