Memorable navigation: Assessing the influence of way-finding in spatial clustering

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Abstract. Navigating around an environment and remembering the events that took place within it are crucial cognitive abilities that have been linked to the Hippocampus and medial temporal lobes (MTL). Scene Construction Theory (SCT) has proposed that a function of the Hippocampus is the implicit and continuous construction of scenes to help prediction of upcoming environment. Scenes, as highly efficient means of packaging information, underpin in coordination with other brain regions, episodic memory (EM), spatial navigation, future thinking and perhaps even dreaming and mind-wandering. We inquired the conditions in which spatial contiguity of stimuli influences the organization of memory by examining spatial clustering (SC) phenomenon. In this research, an augmented reality (AR) system was used to test 14 participants in a spatially dependent memory task which assessed the SC differences between active navigators and passive spectators. We confirmed our hypothesis that navigators use spatial information as part of the retrieval process in free recall, as they tended to sequentially recall any two neighboring otherwise unrelated items. We also found a significant correlation between SC and correct recall performance supporting our second hypothesis. These results may be valuable for design of learning applications, especially dealing with large amounts of data. Research on Alzheimer's and other neurodegenerative diseases may also benefit from our approach. Future studies may assess the role of encoding and retrieval modality and participant's use of mnemonic strategies.

Keywords: Episodic memory · Spatial clustering · Scene Construction Theory · Free Recall · Augmented Reality

1 Introduction

As described in Hume's Principles of Association [1], ideas enter into association with one another when they are contiguous in space and time. In the study of human memory, this contiguity effect has been found in studies of free recall, suggesting that a person is more likely to recall words together that are closer together in a list [2]. The contiguity effect appears relatively constant, and has been predicted to have long-term effects on memory according to researchers[3]. Whereas a massive body of experimental work has demonstrated the potent

influence of temporal contiguity on the association of ideas, we know little about the conditions in which spatial contiguity of stimuli influences memory.

This study examined whether and how spatial navigation influenced the organization of memory by examining spatial clustering (SC) phenomenon and overall recall performance (ORF), using an ecologically valid experimental environment. Previous research has shown that the neural mechanisms of EM and navigation in real and mental space are fundamentally the same. It has been proposed that mechanisms of EM have evolved from mechanisms of navigation in the physical world. A clear parallel between allocentric navigation strategies and semantic memory, on one hand, and egocentric strategies and EM on the other has been suggested. Importantly, studies have confirmed that the brain systems involved in guiding navigation, the Hippocampus and entorhinal cortex, are the same that are activated in declarative memory tasks [4], and that the same mechanisms that define unique positions and their relationships in a map can be used to mediate memory for events, objects and living things [5]. Also, the Hippocampus – entorhinal cortex system has the anatomical and physiological properties to account for temporally evolving structures of unrelated data. Recently, Scene Construction Theory (SCT) has pointed that a function of the Hippocampus is the implicit and continuous construction of scenes, a highly efficient format for packaging information, to help prediction of upcoming environment [6–9]. Therefore, we found reasonable to expect that, when spatial information is available at encoding, Hippocampus would form a scene associating the encountered item and spatial context, and that this composite scene would tend to be reinstated at recall. This reinstatement would not only provide the phenomenological experience of remembering, but also help to cue other memories experienced within the same or related spatial contexts.

From this literature overarching questions emerged: Can we derive learning strategies that profit from the mechanisms of scene dependent memory? Can scenes, the highly efficient information-packing method of Hippocampus, inform design criteria for learning applications? We based our approach on prior studies that show how the human memory system associates each new experience within a spatiotemporal context and that this context becomes reactivated when the experience is recalled [2, 10–12]. In this sense, this study aimed to advance our understanding of the conditions in which spatial contiguity of stimuli influences organization of EM, and if spatial organization of memory correlates to increased performance.

If spatial navigation was essential for the formation of the spatiotemporal context of memory for a given stimulus, we hypothesized that, subjects who navigate an environment would exhibit a significant tendency to consecutively recall neighboring items presented therein. We compared these active performances to that of passive spectators of the same journey of presentation of target items. We also hypothesized that participants showing higher rates of spatial clustering (SC) for a navigation task would present enhanced memory performance.

This article summarizes the findings and updates the interpretation of the second pilot experiment of the Master Thesis *Assessing the influence of spatial clustering in free recall* [13].

Following a between subjects design we conducted a pilot experiment in which participants were presented with items in two spatially dependent conditions: Way finding group in which participants were presented via Augmented Reality (AR) with visual items upon arrival at various real-world locations, compared to a guided navigation group in which participants passively spectated the navigation recording of a corresponding matched-pair, featuring a 3D representation of the traversed environment.

To explore the conditions in which spatial contiguity of stimuli influences the organization of memory, we assessed the performance differences between active navigators and passive spectators in a spatially dependent memory task, using behavioral data, spatial clustering factor (SCF), and overall recall factor (ORF) as scores in Immediate (IFR) and delayed free recall (DFR) 24 hours after trial. Regarding the first hypothesis, this study found significant differences in SC between navigators and guided participants. We also found a significant correlation between SC and correct recall performance supporting our second hypothesis.

Our AR framework helped to evidence functioning of recall dynamics in both the guided and way-finding conditions in a ecologically valid and systematic way. We suggested further studies to clarify participants' use of mnemonic techniques and the role of stimuli modality at encoding and retrieval. Advances in this field may benefit the design of AR learning applications and spatial data interaction paradigms, as well as research on cerebral aging and neurodegenerative conditions such as Alzheimer's disease.

2 Background

2.1 Episodic memory

Episodic memory [14] refers to autobiographical memory for events constructed from its what, when, where components, linked together in a coherent spatiotemporal experience. A key feature of episodic memory is its unique role to allow the individual to mentally travel back into her personal past [15, 16]. The precise details that characterize episodic memory have been debated, but there is consensus that time, space and sense of self are key elements [17–21]. From research carried out using functional magnetic resonance imaging (fMRI) we know that a distributed and highly consistent network of brain regions supports memory for past experiences [21, 22]. It has been suggested that episodic memory in the Hippocampus is formed by combining spatial information from the medial entorhinal cortex [23, 24] with non spatial information from the lateral entorhinal cortex [25, 26]. Imaging studies have also illuminated the contributions of distinct prefrontal regions to encoding and retrieval [27–29]. Episodic memory is affected by aging processes [30], and there have been findings of sex differences

in its performance [31, 32], but results are still inconclusive [33]. Recent studies
 126 have helped to establish that these neural systems also support the capacity to
 imagine and to simulate episodes expected to occur in the future [15, 34–36].
 128 The ability to pre experience future events has been referred by some authors
 as prospection [37] and by others as episodic future thinking [38–40]. Consistent
 130 with this approach, neuroimaging studies focused on the brain activity during
 the construction of past and future events, have revealed regions exhibiting com-
 132 mon activity, which included the left portion of the Hippocampus and the right
 occipital gyrus, especially during the elaboration phase, when participants are
 134 focused on generating details about the remembered or imagined event [41, 42].

2.2 Theories of hippocampal function

136 For decades, the Hippocampus and MTL of the mammalian central nervous sys-
 tem have been structures closely associated with memory [43–46]. Indeed, studies
 138 on Amnesiac and hippocampal excised patients has shown that the Hippocampus
 is essential for acquiring and consolidating new knowledge about events, people,
 140 and places. Several theories regarding the role of the Hippocampus in memory
 have been proposed over the years. All regard the Hippocampus as being critical
 142 for EM, but there are key differences between its mediator or storage roles.

Declarative Theory [47, 48] The Hippocampus, acting together with other me-
 144 dial temporal lobe regions, is crucial for all forms of consciously accessible mem-
 ory processes (episodic and semantic, recollection and familiarity) for a time-
 146 limited period. Ultimately all memories are consolidated to neocortical sites.

Multiple-Trace Theory [49] The Hippocampus, together with other medial
 148 temporal lobe regions, is crucial for the acquisition of episodic and semantic
 memories. The recollection of episodic memories remains dependent on the Hip-
 150 pocampus for the duration of one’s life and becomes more resistant to partial
 damage with repetition and/or rehearsal, whereas semantic memories become
 152 independent of the Hippocampus and are stored in other brain regions over
 time.

Dual-Process Theory [50, 51] The Hippocampus is crucial for episodic recollec-
 154 tion of the contextual details of an event. Familiarity-based recognition processes
 156 are subserved by other medial temporal lobe regions. Recollection is required for
 the associative recognition of non-unitized items.

Cognitive-Map Theory [52] A primary role of the mammalian Hippocampus
 158 is to construct and store allocentric representations of locations in the envi-
 160 ronment to aid flexible navigation, for example, from a new starting position.
 In humans these predominantly spatial processes have evolved to support the
 162 spatio-temporal context of episodic memories.

Relational Theory [53, 54] Attempts to unify the declarative and spatial func-
 164 tions of the Hippocampus, suggesting a broader characterization including both
 functions: that the Hippocampus encodes relational information that can be
 166 flexibly applied to new situations. Thus it claims that the Hippocampus allows

the flexible association of information in neocortical modules that could not otherwise communicate. This enables the relations between elements of a scene or event to be retrieved or used for inference in novel situations, in addition to retrieval of the elements themselves. The Cognitive-Map Theory can be subsumed as a special case of spatial relational processing.

Scene Construction Theory (SCT) [6–8] SCT suggests that a function of the Hippocampus is the implicit and continuous construction of scenes to help prediction of upcoming environment. It does not suggest that the Hippocampus is solely responsible for EM, future thinking, and spatial navigation, but rather that the Hippocampus supplies the crucial ingredient of scene construction. SCT was originally proposed following the observation that patients with hippocampal damage and amnesia are unable to imagine scenes. Scenes are a highly efficient means of packaging information, that underpin and support -in coordination with other brain regions- EM, spatial navigation, future thinking and perhaps even dreaming and mind-wandering. Evidences from this hippocampal scene construction activity come from Boundary extension (BE) studies. BE is a robust and consistent cognitive phenomenon where we erroneously remember seeing more of a scene than was present in sensory input [55]. Accumulating evidence obtained by a variety of paradigms [56, 57] has shown that BE depends on the hippocampal ability to construct scenes. Predictive scene extension processes have been shown attenuated in hippocampal damaged patients, as they significantly reduced BE relative to matched controls across a number of independent measures. These data in addition to the original scene construction findings [6–8], support the idea that the primary function of the Hippocampus may not be mnemonic [58] but may instead be to predict the nature of the world beyond the immediate sensorium [9].

3 Navigation

Navigating is the cognitive process of planning and following routes to travel from the current location to a target location. It involves way-finding, a fundamental human cognitive function, and motoric functions. Way-finding in complex environments relies on complex multisensory perceptual processes, from idiothetic and allothetic sources, and on memory [59–61]. When humans navigate, learn about the environment, by receiving spatial information from multiple sensory cues which are to be stored and used to guide subsequent navigation behavior. Consistent with Tolman’s description of a cognitive-like map of the environment, the conception common to O’Keefe [52] and most researchers on cognitive maps, is that the Hippocampus mediates a holistic representation of space [62]. It has been shown that the spatially selective firing properties of rat hippocampal place cells are controlled by the salient sensory cues in the environment [63]. Research by Siegel and White [64] has provided a description of the process of the construction of a cognitive map as a person becomes familiar with an environment. A cognitive map begins as a set of landmarks, then it is followed by a representation of the routes, meaning the sequence of actions needed to get from one

location to another. Finally, these sequences of actions or routes are united into an internal representation of the environment that is similar to a map, called a survey representation, which is useful because it can be used to generate novel routes between two locations within the environment. The resulting map would be Cartesian in that it provides metrics for the representation of distances and angles between the relevant stimuli. At the physiological level, a place cell reflects as a pointer, the occurrence of the organism at a particular coordinate position within the map. The formation of numerous independent maps in the Hippocampus has obvious advantages for memory formation, as it allows the network to store new representations in a manner that minimizes interference with previously stored memories. The orthogonal nature of hippocampal representations is expressed in its ability to remap between experiences and environments. Even minor changes in the configuration of landmarks or the motivational context can completely alter the firing pattern of the hippocampal cell population. As a result, each environment can be represented by a unique combination of active cells.

3.1 Navigation Strategies

Human navigation is based on two interlinked strategies for encoding and representation of the spatial environment [65, 66].

Allocentric Allocentric navigation is a mechanism that uses the spatial relationships among landmarks in order to define actual location in the environment and to provide static position information in a reference frame. Space representations in this system, may be updated frequently by changes in the configuration of multi sensory inputs.

Egocentric navigation A system which requires active movement of the body, and computes the distances and coordinates based on integration of motion and knowledge of previous positions, thus producing the spatial metric needed for the estimation of distances between landmarks [67]. To that end, egocentric navigation system relies on locomotion speed, elapsed time, head direction and the initial reference position. Allocentric and egocentric navigation always work together, but the availability of external landmarks may determine whether allocentric or egocentric strategies dominate.

3.2 Way-finding

A goal-seeking behavior, using allocentric and egocentric mechanisms, where the navigator must explore and fix the coordinates of his actual location, and compute the difference between his present coordinates and the goal coordinates to obtain the difference vector specifying the direction and distance to move from its current location to its goal [68, 69].

248 3.3 Neural substrate supporting spatial navigation

250 Navigating around an environment is a crucial cognitive ability that has been
 252 linked to the Hippocampus and medial temporal lobes. While processing of spa-
 254 tial scenes involves the paraHippocampus, the right Hippocampus appears par-
 ticularly involved in memory for locations within an environment, with the left
 Hippocampus more involved in EM, context-dependent autobiographical mem-
 ory [70, 71].

Place Cells [72]. Fire selectively when the animal is in one particular region of
 256 the environment. It doesn't depend on the direction the animal is facing [62].
 Firing persists in the dark [73], ruling out an explanation based on simple visual
 258 stimuli correlated with place. Different place cells fire in different environmental
 locations. The place cells are driven by a combination of perceptual inputs and
 260 self-motion information, either of which can individually update the place-cell
 representation. Once established, place cells can have the same firing pattern for
 262 months [74]. The firing patterns can persist even when all of the spatial cues
 are removed. Besides responding to incoming perceptual information, place cells
 264 are also driven by self-motion signals (proprioceptive, vestibular and reafferent
 signals from intended movements), which indicate the location of the animal
 266 on the basis of its own movements. There is an extensive literature describing
 characteristics of place cells in dorsal hippocampal area CA1 [5, 75]. Less is
 268 known about the place code in other medial temporal lobe structures. It is
 known that there are place cells in the entorhinal cortex [76, 77], a region of
 270 cortex that provides input to the Hippocampus proper.

Grid cells [23, 78]. Grid Cells do not represent particular locations in the envi-
 272 ronment. Instead, they tile the environment, and are re-used over and over, like
 the intersections on graph paper. Grid cells have different periodic spacings, and
 274 it is believed that collectively, they form a universal, flexible code for mapping
 otherwise undifferentiated navigable space. Grid cells have multiple firing fields
 276 that span the entire available space in a periodic hexagonal pattern, which pro-
 vides a metric to the neural representation of space. This type of cells system is
 278 present throughout the medial entorhinal cortex and in the pre and parasubicu-
 lum [79]. The correlation structure of grid cells is preserved during sleep periods
 280 [80].

Head direction cells [81] Their firing represents the direction in which the
 282 animal is heading, independent of its current location and the firing direction is
 controlled by self-motion and perceptual information. Head-direction cells show
 284 pattern completion and accommodation for missing cues, and probably set the
 environmental orientation of the responses of place cells. When stimulated, these
 286 neurons fire at a steady rate not showing adaptation, but decrease back to their
 baseline rates as the animal's head turns away more than 45 degrees from an
 288 specific direction [82]. These cells are found in many brain areas, including the
 post-subiculum, retrosplenial cortex, the thalamus (the anterior and the lateral
 290 dorsal thalamic nuclei), lateral mammillary nucleus, dorsal tegmental nucleus,
 striatum and entorhinal cortex [83].

Border Cells. O’Keefe and Burgess [84] observed that the medial entorhinal cortex contains a smaller number of border cells, which line up in specific orientations along specific geometric boundaries of the environment. These cell types were all discovered in rats, but place cells, grid cells and head direction cells have since been found in other species. Border cells may assist in the assessment of the allocentric distances by triangulation and perhaps in scaling the grid size to accommodate to the size of the discoverable environment [85].

4 Space and memory connection: Spatial Clustering

Most theories of memory search assume that the just-recalled item, and its associated semantic and contextual information, forms part of the retrieval cue for the next response. For instance, temporal clustering effects have been observed to the extent that recalling an item retrieves its associated temporal context, as this information will be similar to the contexts associated with neighboring list items [3, 12]. Similarly, SC effects should be observed to the extent that recalling an item retrieves its associated spatial features, as this information would be similar to the spatial features associated with spatially proximate items. Assuming that spatial attributes form an integral part of the item representations encoded in memory, it is reasonable to expect to see SC even in tasks where participants are not instructed to encode the spatial context of the to-be-learned items and where retrieval makes no explicit reference to the spatial characteristics of the items.

The key properties of EM involve binding disparate and often arbitrary details together into a coherent event and the recollection of self-centered past experiences in the context of time and space in which the events occurred [8].

Theories of EM suggest that memory encoding and retrieval are facilitated by spatiotemporal context: a continually updated representation of location in space and time. The Hippocampus appears to have neurons that are specialized for encoding both spatial and temporal information. Hippocampal place cells fire at specific locations within an environment [79], and recently documented hippocampal time cells fire at specific temporal intervals between distinct events [86]. Recent studies seek to examine the role of spatial context in human EM retrieval through a hybrid spatial and EM task. Miller et al. [87] identified place cells as neurosurgical patients performed a delivery task which required them to deliver items to different stores in a virtual town. Following this navigation task, patients were asked to freely recall the items they had delivered. Place cell activation patterns during the navigational task were then compared to the subsequent activation patterns that occurred during the free recall task. Miller found that neural activity during the retrieval of each delivered item was similar to the neural activity associated with the location where that item was encoded. These findings demonstrate context-specific reinstatement of place-responsive cell activity at the time of recall, supporting theories that implicate contextual reinstatement as the basis for memory retrieval [87]. Kahana and others [88] have found neural evidence for contextual reinstatement in humans. After studying a

list of 20 words and performing a brief distraction task, a participant recalls as many words as he can remember, in any order. ECG activity is recorded during each study and recall event. Participants exhibiting stronger neural signatures of context reinstatement also exhibited more pronounced temporal contiguity effects [89]. Another example is the [90] findings on the reactivation of encoding-related brain activity during memory retrieval. Howard et al [91] analyzed the firing rates of ensembles of individual neurons as neurosurgical patients implanted with hippocampal depth electrodes performed a continuous recognition memory task. They found that the ensemble similarity of neural activity when a photograph was repeated was similar to the neural activity recorded during the encoding of neighboring photos.

5 Method

Following a between subjects design we conducted a pilot experiment in which participants were presented with items in two spatially dependent conditions: Way finding group in which participants were presented via AR with visual items upon arrival at various real-world locations, compared to a guided navigation group in which participants passively spectated the navigation recording of a corresponding matched-pair, featuring a 3D representation of the traversed environment. We aimed to avoid semantic and temporal clustering strategies between subjects by presenting with identical target items in the same inter stimuli time span.

We developed an AR system that enabled users in the way-finding group to freely explore Poble Nou Central Park where they were presented with virtual items upon arrival at various real-world locations. Our AR system navigation recording features, used to replay a 3D representation of the way-finding sessions to the matched-paired participants in the guided condition. We measured ORF scores in IFR and DFR 24 hours after trial. We calculated SCF from the logged navigational data. Comparisons were made regarding SCF in the two experimental conditions. We inquired whether subjects higher SCF scores were more prone to higher ORFs.

5.1 Hypotheses

The study was based on prior studies that show that recall dynamics is guided by item and context similarity [92], that SC exists in a two-dimensional environment [93], and that the EM system associates each new experience within a spatiotemporal context and that this context becomes reactivated when the experience is recalled [10, 87, 94].

We reasoned that the spatial conditions in which an item is experienced would form a composite scene for the item, even if the item itself had no spatial information associated with it prior to the experiment. In this sense, when a memory is retrieved, its spatiotemporal context is partially reinstated. This reinstatement would not only provide the phenomenological experience of remembering,

but also help to cue other memories experienced within the same or related spatiotemporal contexts. Therefore, in a task where participants were instructed to navigate around an environment and encode each object in a specific real-world location, it was reasonable to expect that recalling an item would reinstate its spatiotemporal context including nearby items in SC. In the case of being guided as static spectators, there would be less available spatial information at encoding time of the EM scene, thus, other clustering strategies (temporal, categorical) would organize recall.

We hypothesized that participants in the way-finding group would exhibit a significant difference to consecutively recall items presented in spatially proximate locations when compared to passive spectators. We also hypothesized that participants showing higher rates of SC would also show better memory performance. Overall, when participants recalled an item, we expected that the item will evoke its spatial context and thus enhance retrieval of unrelated items experienced in nearby spatial locations.

5.2 Subjects

We interviewed 29 volunteers from Universitat Pompeu Fabra at Poble Nou Campus in Barcelona. We then selected 7 matched pairs in terms of sex and previous knowledge of the experimental location. 14 participants (2 female) aged from 19 to 33 agreed to take part in this study and were assigned each to one of two groups, way-finding condition and guided condition. All participants reported user level experience with AR systems. All were right handed and none wore corrective lenses during the study.

Way-finding Condition Participants were required to explore the physical environment, deciding by themselves the path to follow, using a handheld AR system, which presented 17 virtual landmarks available only for one time display. In our AR system, way-finding was supported by adding virtual landmarks at selected positions of the physical space and rendering target items upon subject arrival.

Guided Condition Participants are presented with a realistic 3D representation of the Poble Nou Central Park, that replayed a session of the way-finding Condition. Participants watched the entire navigation for the same amount of time, with equal inter stimuli time span, and have the target items presented in similar conditions. We take into consideration that previous studies [87] have achieved SC by playing a video game portraying a detailed 3D model.

5.3 AR system

In order to convey a realistic and ecologically valid spatial experience, we developed an AR system using Unity software which enabled to overlay virtual information in real world positions according to participants' spatial coordinates (GPS) and orientation. This system was installed on an Apple iPad model MD369TY/A with 2048 x 1536 pixels visual display and used the built-in GPS

Fig. 1. Overview of two experimental conditions. The AR paradigm used for the Way-Finding condition in the left image. A 3D virtual representation of the journey used for the guided Condition.

receiver. The AR system allowed us to present to participants, 17 virtual landmarks distributed over the physical space. This approach enabled participants to decide the path to follow, navigate and find their way through the space. Each time a participant arrived at the coordinate-defined physical location where the virtual landmark was placed the system presented a virtual target item on the handheld device display. Our system recorded all position and orientation transformations, and user interactions with target items during each experimental session, in order to be replayed for each of the guided condition participants with identical order, visual spatial information, and inter stimuli time span.

Location. Our study took place at Poble Nou Central Park, designed by architect Jean Nouvel and built in 2008. Our study was conducted in a 170 meter long by 60 meter wide area, comprising different landscape and architectural elements, such as gravel, ground, grass and cork flooring, an area with salient trees, two wooden huts, a brick chimney, and several children playground areas. Each of these features was accurately rendered in our 3D representation of the environment.

Virtual landmarks. 17 colorful virtual landmarks, equivalent size of 7 meter height and half a meter diameter cylinders, were placed in AR related to real-world locations. Each indicated a three meter equivalent radius interactive area where the user found a target item upon arrival. Virtual landmarks held no noticeable distinction from each other. The layout of the park and the location of the virtual landmarks was identical for every participant.

Target items. 17 items from the Moreno-Martinez and Montoro [95] alternative to Snodgrass & Vanderwart [96] object image databank were selected to be presented to participants. These pre validated pictures were semantically significant everyday objects, rendered in a realistic appearance in 1024px wide by 768px height and 72 ppi on the AR visual display, with item name captioned in 60px Sans Serif type. Any of the 17 target items only became visible for a 5 second

period when the participant physically walked into any of the three meter radius interactive areas indicated by the virtual landmarks.

Real - Virtual Landmark connections. We chose to locate each virtual landmark near existing architectural landmarks found at Poble Nou Central Park. Target items and physical landmarks held no semantical relation, as virtual target items were randomly allocated.

Fig. 2. Left, an orthographic image from the experimental location, and overlay of virtual landmarks and target items. Left, Virtual target items were distributed near existing architectural landmarks at Poble Nou Central Park.

5.4 Procedure

Before the start of each session, participants were given written instructions explaining the procedures to take place, and asked to give signed consent in order to begin the trial. Then, participants were guided through a 2 minute familiarization process with the AR system. Finally, participants were led to the trial starting position, defined at latitude 41.407221 and longitude 2.199322 which was set to be position $X=0$, $Y=0$ in our fixed coordinate system across trials. Maximum duration of the procedure was 35 minutes.

458 **Way-finding condition.** The participants in the way-finding condition were
 460 asked to physically explore the real park environment during a maximum of
 20 minutes using a hand-held device that allowed virtual landmarks and target
 462 items to be presented in AR. All 17 virtual landmarks are visible from the start,
 indicating real world locations where users were to find virtual target items.

Guided condition. In the Second Pilot Experiment, participants sat down at
 464 local coordinates $X=0$, $Y=0$, and were presented with a realistic 3D representa-
 tion of the corresponding recorded session of a way-finding journey. Participants
 466 watched the entire navigation for the same amount of time and inter stimuli time
 span, and had the target items presented using the same display and in similar
 468 viewing conditions.

5.5 Data Analysis

470 **Immediate and Delayed Free recall** Free recall tasks allowed us to measure the
 way participants organize learned items [97–99]. EM was investigated by visually
 472 presenting items for study, and then asking participants to recall the items. Using
 a method for measuring SC modified from previous studies [87] we could quantify
 474 the way in which people transition from one recalled item to the next. For that
 reason, participants from both way-finding and guided conditions completed an
 476 IFR task, in which they were asked to verbally report as many recalled items
 as possible, in any order, for 90 seconds. 24 hours past from the experimental
 478 procedure, each participant was called by telephone to be questioned about the
 target items they were able to remember in free recall during 90 seconds in order
 480 to complete a DFR task. Recalled items were considered valid only if reported
 once and if they were actually presented to participant.

482 **Spatial clustering factor.** To determine whether the spatial proximity between
 items had an effect on the order in which items were recalled, we compare the
 484 SCF for each recalled item by each participant in the way-finding condition, to
 similar data from the guided condition. In order to establish a SCF for each of
 486 the reported recalled items, both in IFR as in DFR tasks for all participants, we
 compare the distances between a recalled item position and the position of the
 488 next recalled item. We used a custom version of the Haversine formula imple-
 mented in Python programming language. Then, we compared this measurement
 490 to the distance between a recalled item position and each of the available possi-
 bilities in the target item pool. A SFC of 1 was assigned to the most proximal
 492 locations between any given pair of items in the entire pool of items, whereas all
 other transitions between locations will receive proportional SFC values with 0
 494 as a lower bound.

Spatial clustering and overall recall performance. To determine the impact
 496 of SC in overall recall performance, we first calculated the ORF of each session
 by defining the percentage of valid items recalled from the total of presented
 498 items. Then we normalized each percentage value to decimal range. To obtain
 an ORF of 1, all presented items during a session would have had to be recalled.

At this point we conducted a Correlation Test between the ORF and the SCF average of each session to assess the influence of SC on recall performance.

6 Results

The sample for the Second Pilot Experiment consisted of 14 subjects (2 females) paired-matched and distributed in two groups, the way-finding and guided conditions. The mean age of participants equaled 25 years (average SD=1.1). From the 17 target item pool that the procedure asked to be found, participants in the experimental condition scored a mean of 11,25 in target item findings. Results for the Kolmogorov-Smirnov test for normality indicated that the SCF distribution in way-finding deviated significantly from a normal distribution for IFR ($p<.001$) and DFR ($p=.024$). We then conducted Kolmogorov-Smirnov test for normality for ORF scores, which indicated that the ORF distribution did not deviate significantly from a normal distribution ($p=.200$).

Comparing SC in way-finding and guided conditions. A Mann-Whitney 2 tailed U test was conducted to compare the SCF for way-finding and guided conditions in both IFR and DFR tasks. We found statistically significant differences in both in IFR $U=561$, $p<.001$ and in DFR $U=453.5$, $p=.036$.

Correlations between SFC and Memory Performance A Pearson product-moment correlation coefficient was computed taking the complete set of free recall tasks to assess the relationship between the OFR scores obtained in each session and a SFC average of each session. We found a positive correlation between the two variables $r = .499$; $p = .007$. A Pearson product-moment correlation coefficient was computed considering only the DFR results to assess the relationship between the scores of recalled items obtained in each session's OFR and a SFC average score. There was a significant correlation between the two variables $r = .607$; $p=.021$. Computing a Pearson product-moment correlation coefficient only considering the results from IFR we found no statistically significant correlation between the two $r = .108$; $p=.497$.

7 Discussion

In recalling a list of previously experienced items, evidence has shown that humans organize their responses on the basis of the items' semantic and temporal similarities. This study aimed to shed light on the conditions in which spatial contiguity of stimuli influences the organization of memory.

If spatial navigation is essential for the formation of the spatiotemporal context of memory for a given stimulus, we hypothesized that, subjects who navigate an environment in the way-finding condition would exhibit a significant tendency to show SC in consecutively recalling neighboring items presented therein.

We also hypothesized that participants showing higher rates of SC during a navigation task would also show enhanced memory performance.

Following a between subjects design we conducted a pilot experiment in which participants were presented with items in two spatially dependent conditions: Way finding group in which participants are presented via AR with target visual items upon arrival at various real-world locations, and a guided condition in which participants passively spectate the navigation recording of a corresponding matched-pair from $X=0, Y=0$ local coordinates of the same environment. We assessed the performance differences between active navigators and passive spectators measured in SFC and ORF using behavioral data and scores obtained via IFR and DFR.

Wayfinding significantly increased SC Regarding the first hypothesis, we evaluated whether a correlation between SC and navigation paradigm existed and found significant differences in SC favoring wayfinders. We found that navigation played a crucial role in the formation of context-based memories. As such, the target items encountered during navigation became associated with their spatiotemporal context at encoding. And when this memory was retrieved, the spatiotemporal context of the encoding episode was also reinstated. This reinstatement not only provided the phenomenological experience of remembering, but also helped to cue other memories experienced within related spatiotemporal contexts. We suggest the need for future research to address the roles of decision making and sensorimotor components of navigation and their contribution to SC.

SC significantly increased ORF For our hypothesis regarding enhanced memory performance, we found a significant positive correlation between SC and ORF $r = .499$; $p = .007$. However when grouping only IFR results, this effect was significantly attenuated. We suggest the need for future studies that clarify if participants employed a non spatial mnemonic strategy that obfuscated the influence of SC in IFR.

Overall these results have confirmed previous studies that found that the EM system associates each new experience within a spatiotemporal context and that this context becomes reactivated when the experience is recalled [87, 10, 2]. These results must be interpreted with caution as we are aware that a major topic of discussion for the validity of our results is the limited size of the sample.

Our AR framework proved to be adequate for analysis of the relation between space and memory because it helped evidence in a systematic, coherent and exhaustive way the structure and functioning of recall dynamics in both the guided and way-finding conditions. For the participants in the way-finding Condition using the AR system and the hand held device demonstrated to be an intuitive and straightforward task. Although our system accuracy needs further improvements, the overall dynamics and interactions with virtual contents are fluent and stable. Further improvements to the AR system and the handheld device could explore ways to device more precision in GPS readings and a greater refresh frequency for a more fluent interaction with the environment. Because of the use of current GPS technology this experiment can not take place indoors, which also could be a matter of research. Regarding the rendering qualities of the guided condition group we suggest further research must be done comparing the

584 suitability of the realistic 3D virtual for our research needs, and compare to other
 586 rendering solutions such as to that of a viewpoint recording of the way-finders
 and its replaying over the guided condition.

We acknowledge the need to confirm these results by testing a greater partic-
 588 ipant population. An extension of this study may address the use of spa-
 tial mnemonic strategies, whether and how humans prefer spatial organizational
 590 strategies over temporal or categorical strategies. We also suggest further re-
 search on the role of encoding and retrieval modality [99] and the use of multi
 592 modal tasks. This field of research has interesting implications for the design of
 learning applications that could profit from spatial distribution of contents and
 594 exploratory learning behaviors. Our approach also presented potential benefits
 for memory studies and research on cerebral aging and neurodegenerative dis-
 596 eases. For instance, in Alzheimer’s disease deficits in EM function are among the
 first cognitive symptoms observed and its study in ecologically valid tasks may
 598 be of profit. Furthermore, impaired EM function is also observed in a variety of
 other neuropsychiatric diseases including dissociative disorders, schizophrenia,
 600 and Parkinson’s disease.

Taking a different approach, several recent fMRI studies compared recall of
 602 autobiographical memories with predicting possible personally relevant future
 events known as episodic future thinking [38], and found near complete overlap
 604 in the brain networks activated [100, 101]. This scenario could provide ground
 for questioning the nature of SC in episodic future thinking. And also on the
 606 process of imagination as recent studies suggest that there are common processes
 in both EM and creative imagination, which can be characterized by the concept
 608 of scene construction [6]. If the Hippocampus plays a critical integrative role in
 a constructive process such as recollection it seems plausible that SC might also
 610 have a role in supporting the imagination, and in predicting the future [21].

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