Improved spatial memory for physical versus virtual navigation

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Highlights

- Participants performed a spatial memory task while physically walking vs. while stationary in front of a computer.
- Participants found the ambulatory condition easier, more immersive and more fun.
- Objectively, participants are significantly more accurate in error distance when moving compared to stationary.
- In a case study, a patient with a chronic neural implant continuously streaming anterior nucleus of thalamus and hippocampal local field potentials performed these tasks, and the recordings demonstrate that neural representations of movement are stronger during physical movement.

Abstract

Spatial memory is a crucial part of our lives. In recent years virtual reality has become a key tool for research into spatial memory. Virtual environments offer many advantages in terms of logistics, combination with neuroimaging and more. However, due to interface limitations in the vast majority of this research participants were stationary. It is well established in animal models that the lack of physical movement in virtual reality impairs some neural representations of space, and this is considered likely to be true in humans as well. However, it is unclear how big this effect actually is - exactly how much does physical movement during encoding and recall affect human spatial memory? Additionally, it is unclear what effect the fatigue of actually walking during the task will have on participants - will it decrease their performance, and possibly increase their perception of difficulty?

Here we utilize augmented reality to enable participants to perform a spatial memory task while physically moving in the real world compared to a matched virtual reality task performed in a stationary fashion. Although participants showed good performance in both conditions, they reported that the walking condition was significantly easier, more immersive, and more fun than when stationary. Importantly, memory performance was significantly better in walking compared to stationary.

We augment these results in ambulatory human participants with a case study of a patient with an investigational chronic neural implant (Medtronic Summit RC+S™) streaming real-time continuous hippocampal local field potential data while performing the same spatial memory task. We show evidence for an increase in the amplitude of the neural oscillations associated with movement when moving through the physical world as compared to moving virtually.

Our findings validate that integrating AR can lead to improved techniques for spatial memory research and highlight the importance of paradigms that include physical movement to research in this field.

Keywords

Spatial Memory, Navigation, Physical movement, Augmented Reality, Virtual Reality

Introduction

Where did I leave my keys? Where did I park my car? As we go about our day we are constantly faced with spatial memory tasks, in which we form and utilize associations between various objects and specific locations. To understand how spatial memory works, one can perform experiments in the real world, by placing items in different locations and asking participants to remember a given object's location. Such experiments are inherently cumbersome in the real-world —e.g. to test spatial memory for multiple items in different locations one would need to collect those items, manually position them around the environment for each trial, all while being restricted by physical limitations such as the available environment, equipment, the need to do so silently without tipping off the participants etc. These technical difficulties have led to the popular use of virtual environment based paradigms for studying spatial memory (e.g. [1], [2], [3]). The vast majority of this work utilizes desktop based environments rather than via immersive headsets as these older-style environments are simpler to use and run, do not require dedicated hardware interfaces, and are more compatible with neuroimaging and physiological recording. This use of virtual environments raises an important challenge – are spatial memory and navigation within them really the same as in the real world?

Desktop based virtual environments lack the physical motion, level of immersion, and idiothetic (internal self-motion) cues of real-world navigation, which may lead to differences in performance (e.g.,[3], [4], [5]). Beyond impairing the environment's perceived realism, these missing aspects may lead to changes or disruptions in the underlying neural processes and evolutionary evolved mechanisms for spatial memory (e.g. [3], [6]). Indeed, results from animal models demonstrate that spatial signals might be disrupted or degraded in virtual environments. While these challenges are clearly there, the extent of the actual differences they lead to in terms of spatial memory accuracy in humans is less clear, and thus it is unclear how good of a model for natural behavior these stationary paradigms are compared to natural ambulatory behavior - How important is it to perform the experiment's in the real world while actually moving? Are these differences significant?

Augmented reality (AR) has recently emerged as a powerful new tool to enable spatial-memory paradigms in the real world which include physical movement [7], [8]. When using AR, a user views virtual (or "augmented") objects overlaid on the real world, and this hybrid environment can be viewed via dedicated interfaces such as head mounted displays and smart-glasses, or via commonplace interfaces such as smartphones, and tablets [7], [9]. This enables users to walk around any environment, which can be augmented via computational means with targets, landmarks and more. Thus, AR offers a solution for studying spatial memory with the advantages of both real world and virtual paradigms. It allows users to naturally move through their environments, while also providing experimenters precise flexibility and control by having virtual objects and landmarks placed at controlled locations within a real environment with experiment controlled timing. Previous work on AR and spatial memory is limited - Juan et al. [10] ran an augmented-reality spatial memory test for children, and showed that it elicits performance patterns that correlate with those seen with more traditional measures. However, this study was limited by the use of fixed physical points for augmented objects via QR codes, and did not compare participant's performance to a matched virtual version of the same task. Similarly, Khademi [11] and Hondori [12] used AR for spatial-motor rehabilitation, but did not include a memory element or a direct comparison to VR. Given AR's potential, we aim here to study empirically whether the ability to walk around in an AR paradigm leads to differences in spatial memory performance compared to a classic stationary VR version of the same paradigm in a matched environment. We examined both memory accuracy as well as participants' reports of their engagement and enjoyment in the task versions.

We hypothesized that the use of an AR task, because it includes actual walking, might utilize additional neural systems related to locomotion and internal perception and that this would lead in turn to improved performance and improve the users' subjective experience. However, we also considered that participants might perform better and experience more enjoyment in the desktop VR condition, as physical walking might lead to increased fatigue which in turn could degrade performance.

Although our primary objective here was to compare how spatial memory accuracy shifted between stationary and mobile paradigms, we also tested if patients with chronic epilepsy could perform our ambulatory task, and most importantly compared navigation-related neural signals between the two task versions via a case-study by enrolling a patient in our task who had an investigational implanted brain-recording streaming device.

Methods

Paradigm

We developed matched ambulatory AR and stationary desktop VR versions of the "Treasure Hunt" spatial memory task [13], [14], [15], [16]. Treasure Hunt is an object–location associative memory task in which participants are asked to remember the locations of different hidden objects scattered throughout a virtual environment. Whereas the previous studies had participants perform Treasure Hunt in a tropical beach environment rendered only in virtual reality, here we asked participants to perform the same treasure hunt task in a conference room, matched in both virtual reality and augmented reality implementations (Fig 1).

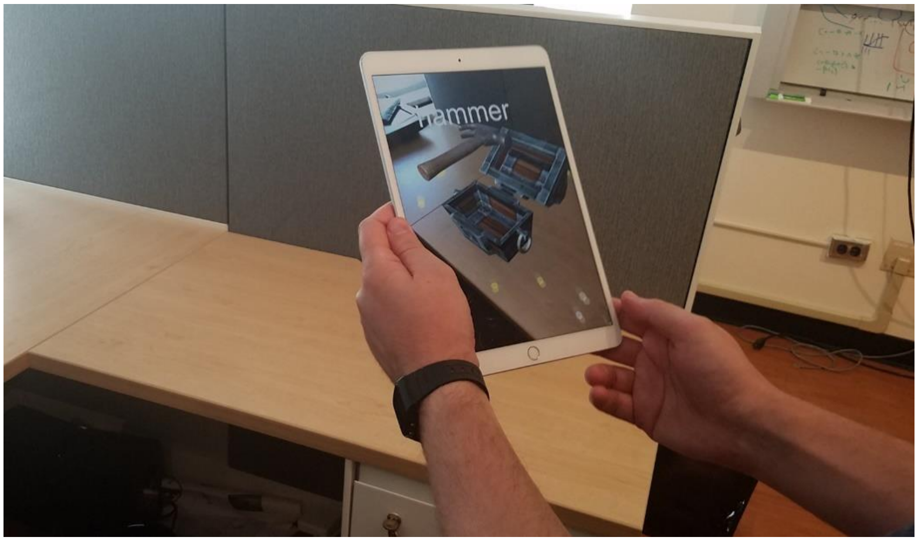

Figure 1. Tablet interface for mobile augmented reality spatial memory task.

In each trial of Treasure Hunt, participants first perform an ***encoding phase*** (Fig 2, Columns 1-2), in which they navigate to a series of treasure chests, each of which is positioned at a random spatial location. When the participant reaches a chest, it opens, revealing an object whose location they are asked to remember. The participant then walks to the next chest. After a series of these learning events, a short ***distractor phase*** begins. Here an animated rabbit runs through the environment, which the participant is instructed to catch. Chasing the animal during the distractor phase serves two purposes, distracting the participant from rehearsing their prior memories and also moving them away from the location of the last remembered object. Next, during the ***retrieval phase*** (Fig 2, Column 3), participants are shown the name and image of each object and asked to respond by walking to and indicating the location where that object was encountered. After recalling the locations of all of the trial's objects, they receive feedback on their response accuracy in the ***feedback phase*** (Fig 2, Column 4). Here the participants view every object's correct location as well as their response location for each object, with lines linking the two. Participants receive points based on their response accuracy and speed in the main spatial-memory task and on their performance on the distractor task.

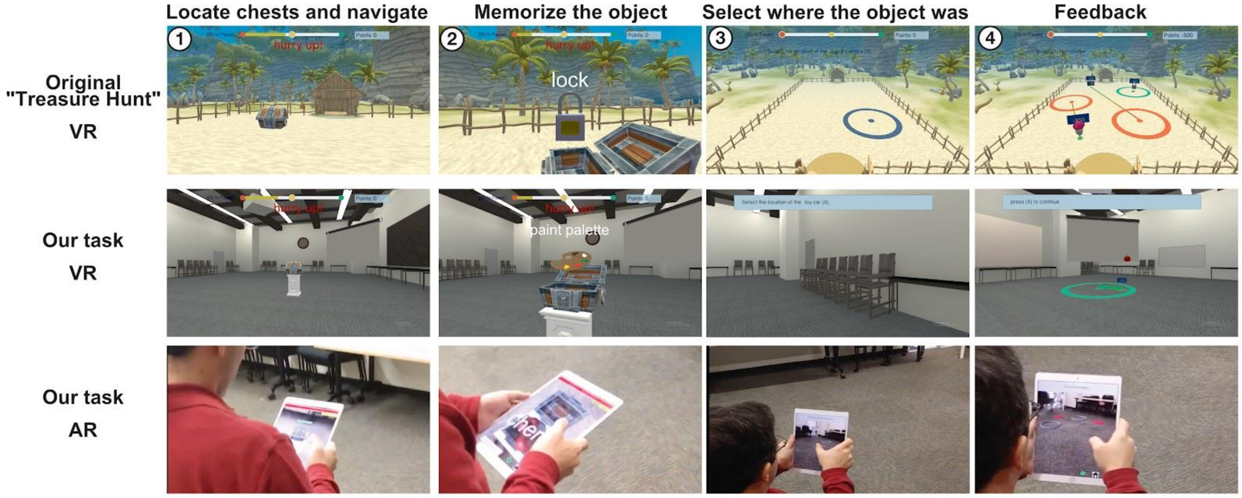

Figure 2. Paradigm. The top row's screenshots are from the classic "Treasure Hunt" task on which we based our paradigm (used in [16]). The middle row is from our adaptation of this task for the one used here in stationary virtual reality, and the bottom row from the mobile Augmented Reality version. In each of these versions, participants perform a series of trials. In each trial they first perform an encoding stage in which they (1) locate 2-4 chests and navigate to them, (2) and then memorize the objects hidden in them. This is followed by a recall stage where participants are cued to (3) mark the location of specific objects and by a feedback stage (4) in which the true location and the participants' selections are revealed.

Participants performed 20 trials of the task in each condition. Each trial probed either 2 or 3 target chests and 1-2 empty chests. Thus, each participant viewed a total of ~50 spatial memory targets for each condition. The overall experiment took participants ~90–120 minutes, including time to complete a questionnaire and to walk between the rooms where the stationary and ambulatory conditions took place. Approximately half of the time was spent on the stationary conditions and half on the ambulatory condition. Participants used a handheld tablet to view the environment with AR in the ambulatory setting and a standard desktop screen and keyboard for the stationary condition.

Implementation

The VR task for the stationary condition. The stationary VR version of Treasure Hunt was developed for Windows using the Unity3D game engine (Unity Systems, USA). We replicated the real-world testing environment used in the mobile AR version of the task using 3D modeling software, such as Blender. During the process of creating a virtual environment that served as a replica of the AR testing environment, we were careful to preserve the dimensions of the room as well as the arrangement of different objects like chairs and tables along the peripheral walls of the environment.

The AR task for the ambulatory condition. The AR version of the task was developed for iPad using Unity3D and ARKit (Apple Inc., USA), the latter of which is Apple's library for allowing development of augmented reality applications for iOS devices [17]. ARKit uses a technique called "*visual-inertial odometry"*, which combines motion sensing information from the accelerometer of the iOS device with computer vision analysis of the scene visible to the back-facing camera. It recognizes notable features in the scene image, tracks differences in the positions of those features across video frames, and compares that information with accelerometer data. Using that information, it is able to track the position of the participant holding the iPad accurately within the augmented reality coordinate space. For the purpose of creating a testing environment for our AR experiment that would align augmented and real-world landmarks in a consistent fashion across sessions, we utilized a feature of ARKit called “world map,” which saves the tracked features of a scene in the form of a point cloud. When this world map is loaded at the beginning of each experiment, ARKit attempts to match the point cloud data with the features currently being tracked. We note that while the current registration process is relatively smooth (typically 10-30s per experiment) it still leaves significant room for improvement and automation in environments under different lighting conditions and outdoors, which is why we chose an indoor environment for this experiment.

Healthy Participants

22 healthy participants performed the experiment. Due to a technical issue, the logs for the AR condition for four participants were not usable. For these participants, we still used their full VR results and their questionnaire answers, but note that excluding them does not significantly change any of our results. Power calculations with power=0.8 and effect size of D=1 show that our sample size is well powered for the analysis performed here. The experiments were approved by Columbia University’s institutional review board (AAAR5000) and all participants gave informed consent and were compensated for their time.

Epilepsy patients

We enrolled 4 additional patients in our study, to verify that patients with chronic epilepsy could indeed perform the ambulatory condition. One of these participants was a patient implanted with an investigational deep brain stimulation sensing system, the investigational Medtronic Summit RC+STM. The RC+S is an experimental implantable device for focal epilepsy with sensing and electrical stimulation capabilities. Compared to other available devices, RC+S has the unique advantage streaming continuous local field potential (LFP) to a distributed cloud computing environment that enables tracking electrophysiology and behavior (clinician, researcher) for intelligently adapting brain stimulation. The major advances of the RC+S include uninterrupted iEEG telemetry of multi-node LFP to an epilepsy patient assistant application (EPAD) for data storage, analysis, and cloud computing [18], [19], [20], [21], [22]. In the context of our current study, it enables chronic neural recording as patients are ambulatory, untethered and can freely walk in natural environments. As a case study, a single patient with a chronically implanted RC+S implant took part in our experiment for proof-of-concept of the task, and to enable exploration of neural representations of spatial behavior while walking virtually vs. walking physically. These patients with drug-resistant mesial temporal lobe epilepsy was enrolled under FDA IDE: G180224 and Mayo Clinic IRB: 18-005483 *Human Safety and Feasibility Study of Neurophysiologically Based Brain State Tracking and Modulation in Focal Epilepsy* https://clinicaltrials.gov/ct2/show/NCT03946618.

Statistics

Corrected error distance. Our main measure of performance was how accurately the participant remembered the location of each object. To measure this, we computed the corrected error distance between the selected location and the target location – i.e. the raw distance for each target, which is the Euclidean distance between the coordinate of the location the participant selected for their response and the actual target object’s coordinate. We then corrected this distance metric following the procedure described in [16], by comparing it to the distances between 100,000 points randomly generated inside the environment and each target and assigning the percentile as the corrected error distance. The corrected error distance is thus the relative rank among these 100,000 distances. This corrects for situations in which different target locations can be biased - e.g., if the target is in the center of a rectangular environment, the maximum error distance is at most half of the diagonal, while for a target in the corner of the environment the maximum distance can be the full diagonal length of the environment. We also extracted the median randomly generated distance as representing the chance level for each trial. We note that repeating our analysis also with the uncorrected distance errors leads to equivalent results.

Statistical comparisons. We first tested the differences in participants' subjective scoring of difficulty, immersion and enjoyment using a signed rack test, since these values were discrete and do not distribute normally. To statistically compare the participants’ memory performance between conditions, we calculated the mean corrected error distance per participant in each condition, and then performed a rank-sum test. To test whether each individual participant performed above chance we used the values described above - the participant’s uncorrected error distance scores and their matching trial-specific chance value generated by taking the distance at 50% in the correction method described in the previous section. We then pairwise tested the relationship between the pairs of selected distances and the surrogate ones using a signed-rank test. Significance levels were corrected via the Bonferroni correction for multiple comparisons. These comparisons enable us to directly test in the next section whether participants' spatial memory performance in each condition was significant and whether physical movement leads to a significant advantage.

Analysis of neural data. The neural LFP data was extracted from the RC+S implant, from the channel in the patients left hippocampus sampled at 250 Hz. Then we used Matlab to interpolate the behavioral data from 60Hz to 250Hz to match the neural data’s sampling rate, and aligned the neural data with the behavioral log to a joint timeseries. We extracted theta power (5-9 Hz) per time point using the Hilbert transform, and then compared mean power during times in which the patient was moving to mean power during times in which the patient was not moving within both the ambulatory and virtual conditions.

Results

In order to understand spatial memory in the real world, healthy participants performed our version of the “Treasure Hunt” spatial memory task in the ambulatory and virtual conditions. Condition order was randomized between participants to avoid order effects of learning on one hand and fatigue on the other. We assessed participant performance by measuring spatial memory accuracy via their performance and user experience via questionnaires. participants also filled out a standard questionnaire that assessed their spatial abilities (The Santa Barbara Sense of Direction scale, SBSoD [23]).

All participants were able to successfully complete the experiment, including walking ~1km within the experiment room during the ambulatory condition.

Performance in each condition separately

We first tested whether participants could perform the task well by assessing whether their memory error was above chance. In the walking condition the mean memory error across participants was 0.08±0.01 (normalized units, 0 representing best memory, 1 representing worst memory). We found that the participants were all able to perform the task significantly above chance (all p’s<10^{-7}). This demonstrated that participants were consistently able to respond at locations relatively close to the actual memory target position.

Next, we measured performance while participants performed the task in the matched stationary condition. We found that here too participants were able to perform the task significantly above chance (mean memory error = 0.16±0.01, all p’s<0.03). We also compared their performance to a wider baseline of data from the standard implementation of the “Treasure Hunt” task from [13] and found that the results were in line with this baseline (p=0.65, unpaired two-tailed t-test). This demonstrates the validity and fit of our task for successful testing spatial memory despite the use of a different virtual environment compared to the earlier studies (as here we used the matched room rather than the beach used in previous work).

Comparing physically walking and stationary virtual walking

We next compared the performance of participants between the ambulatory versus virtual settings. Here we found that participants were significantly more accurate when physically walking than when stationary virtual walking (mean memory error was 0.08±0.01 and 0.16±0.01 respectively, Cohen's D=1.49, $p<0.001$, rank-sum test) (Fig 3) - performance when walking was twice as accurate!

To better understand the source of this improved performance during the ambulatory condition, we compared participants' subjective experiences between the two conditions (Fig. 4). Participants subjectively reported that the ambulatory version was easier (Means = 2.9±1.3, 4.4±0.5 respectively, $p<0.01$), more enjoyable (Means = 3.6±1.1, 2.7±1.1 respectively, $p<0.01$) and more immersive (Means = 3.9±0.9, 3.2±1.1 respectively, $p<0.01$) then the stationary condition. These ratings matched with participants' comments: "Overall, the mobile AR was fun and immersive" S3 "When I feel disconnected from my body, I had difficulty to estimate my location accurately. " S16 "to sense the space in VR is much harder." S22. Note that this preference was there despite the participants needing to physically walk around for 20 minutes, with most covering over a kilometer of real world distance during the ambulatory condition, demonstrating that fatigue was not a serious constraint in our task.

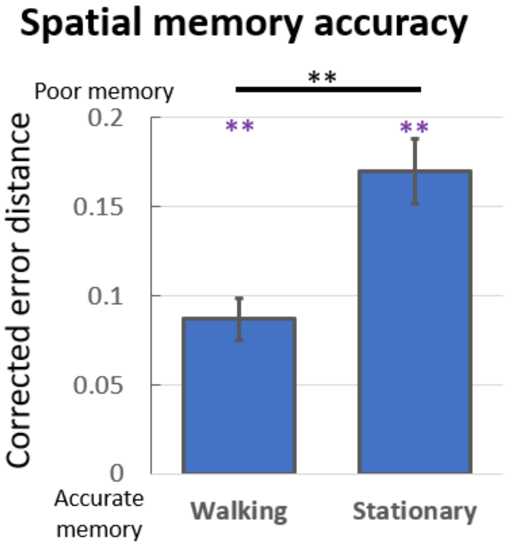

Fig 3. Spatial Memory accuracy. participants showed significant spatial memory in both conditions. When comparing ambulatory walking to stationary virtual walking, we found a significant advantage for physical movement.

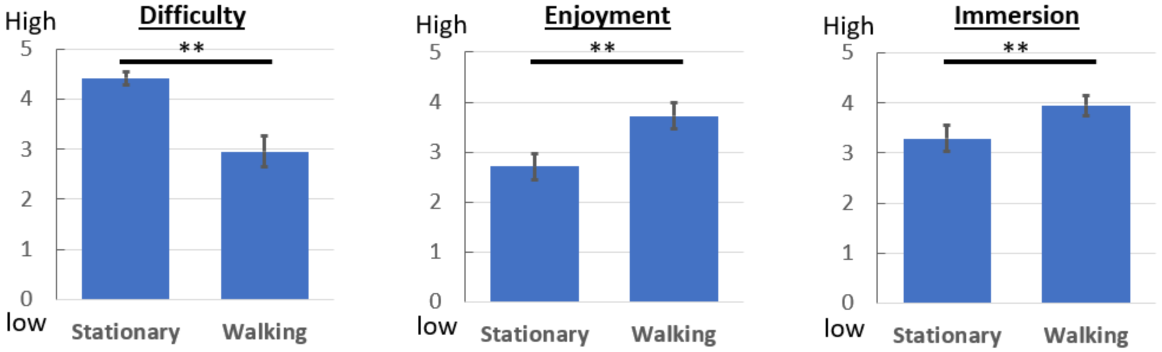

Figure 4. Subjective experience of walking physically vs. virtually. participants subjectively reported that the physical walking condition was significantly easier, more fun and more immersive than the virtual walking condition.

Spatial memory performance and sense of direction. We used the Santa Barbara Sense of Direction (SBSoD) scale questionnaire to assess how each participant perceives their own spatial abilities [23]. This measure has been shown to strongly correlate with many other spatial measures (e.g. [23], [24], [25], [26]). Therefore, we then correlated participants' scores on the Santa Barbara questionnaire with their performance in each of the conditions. We did not find a correlation between SBSoD to performance in the stationary virtual walking condition (r=0.06, p=0.79), but did find a positive correlation with performance for the physical walking condition albeit only at a trend towards significance (r=0.4, p=0.08). This result was also consistent with participant's subjective responses. Several participants reported that physical walking felt closer to natural behavior. For example: "I felt like I was doing something totally different when actually walking, this just felt natural" (S62), "In VR I felt like my body was not connected to my movements and I was totally disconnected" (S45).

Extending results to ambulatory epilepsy patients. Would these results extend also to patients with epilepsy? To test this, we recruited a set of four epilepsy patients as a case study to test if their performance when walking would match the performance distribution of walking or of the stationary conditions. We found that indeed, the four patients were able to perform the task significantly above chance (all p<<0.01), and further that their distribution and performance levels matched that of the ambulatory condition in healthy participants (p=0.68 when compared to ambulatory, p<0.03 significantly better than stationary).

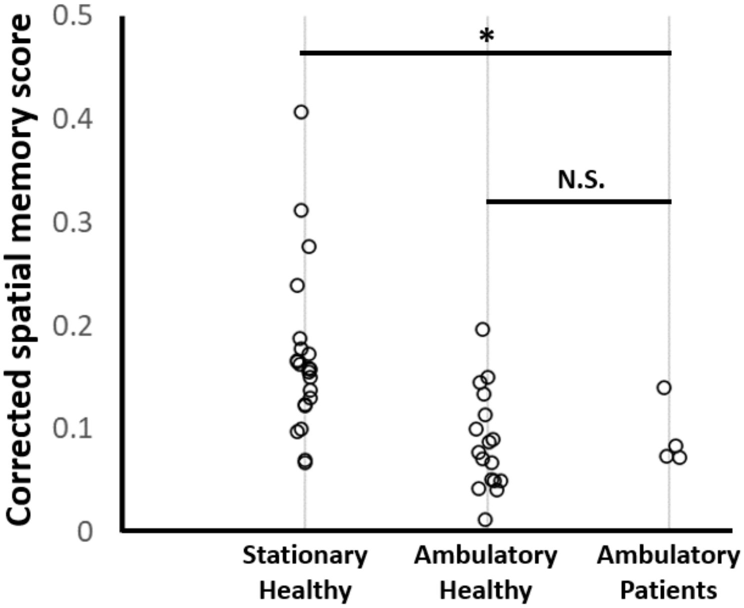

Figure 5. Patients vs. healthy participants. Patient performance in the ambulatory condition matched that of the participants in the ambulatory condition, while being significantly better than performance in the stationary condition.

Neural representation of physical movement. We then asked how moving physically would affect the underlying neural hippocampus LFP signature for movement. A commonly seen neural signal related to movement is the hippocampal theta oscillation, which generally increases in amplitude during movement and navigation compared to periods of stillness [27]. Importantly, while previous work has demonstrated this in humans [28], human theta activity is not as clear as that found in animal models, and often appears in lower frequencies. It has been suggested that this may be due to previous work focusing on recordings during stationary tasks, and indeed this difference appeared during movement in a previous ambulatory task [29], [30], but these previous work unfortunately did not include a matched virtual task. Thus, we hypothesized that for both conditions theta frequency power should be greater during movement, but that this difference should potentially be more pronounced when physically walking. We examined this issue with recordings from a since case study patient who was implanted with a Medtronic RC+S with streaming hippocampus LFP data. Consistent with our predictions, there was greater theta power (5-9Hz) during movement in both the virtual reality and AR versions of the task conditions (Stationary: 2.4 E-9±3.1E-7 vs. 2.2 E-9±1.4E-8 p<<0.01; Ambulatory: 4.9 E-9±4E-7 vs. 4.6 E-9±4.1E-7 p<<0.01). Movement while ambulatory elicited significantly more theta power then moving virtually while stationary (p<<0.01) These results emphasize the potential for AR-based mobile tasks, with real physical rather than virtual movement, to more strongly engage the hippocampal network as indexed via theta rhythms.

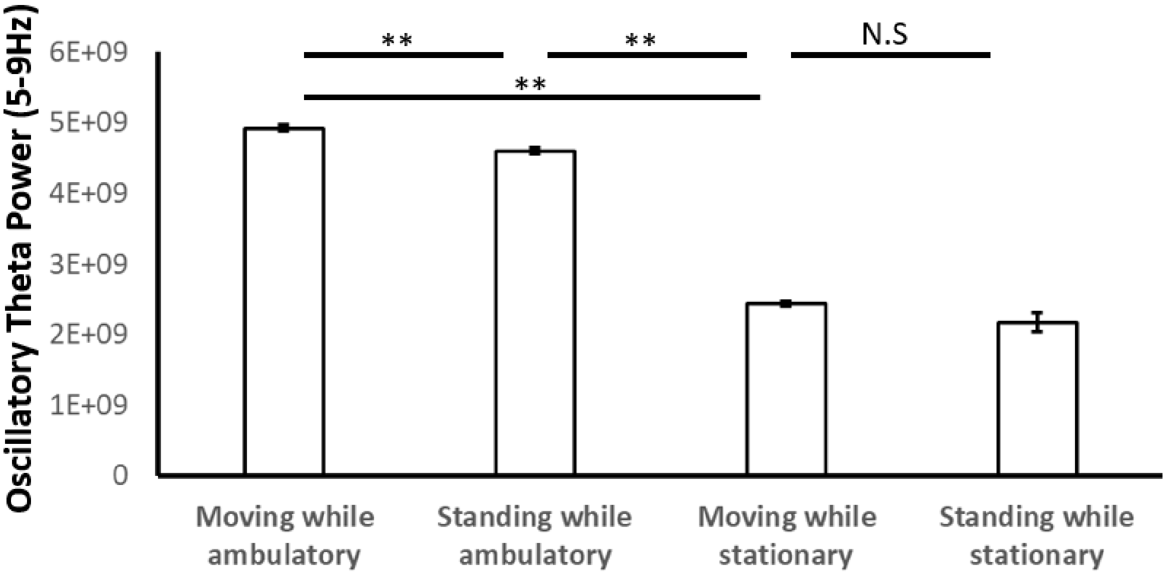

Figure 6. Theta oscillations in stationary vs. ambulatory. Participants displayed increased theta for moving>standing, and the physical walking showed higher theta then virtual walking for both stationary and movement.

Discussion and future work

Our main finding was that when comparing spatial memory directly between performing a spatial memory task while physically walking with an AR interface with performing a matched task with virtual walking on a computer screen, accuracy was twice as good in the condition which included physical walking. Further, participants found the ambulatory version of the task to be significantly easier, more fun, and more immersive. We also found preliminary evidence that this is true not only for spatial memory accuracy but potentially also for the underlying neural signals, extending the work of [29], [30]. These results suggest overall that AR-based navigation tasks may have potential for improving our ability to probe human spatial behavior and the underlying neuroscience. Our results show nearly a doubling of spatial accuracy when participants can physically move, indicating that a critical component is missing in stationary tasks and that there is a need for further naturalistic research in which participants can physically walk about.

The effect of moving on behavior. While we expected improved performance in our task, we also expected this difference to be relatively modest and tempered by effects of fatigue. Instead, our results show a highly significant difference of doubling the accuracy when physically moving. This suggests a gap that needs to be considered carefully in work which relies solely on virtual spatial memory.

Reality modality. Although our results suggest some interesting differences between the conditions, it must be acknowledged that there is a second parameter differing across the conditions - the reality modality. Specifically, the ambulatory condition utilized AR in the real world, while the stationary condition utilized a fully virtual environment. To our knowledge, spatial memory performance has not been directly compared between mobile AR and mobile VR using matched tasks. However, the relationship between AR and VR has been explored for many other realms, with emphasis on education and training. These include testing educational applications, such as teaching about recycling [31], the water cycle [10], multiculturalism [32], forensic medicine [33] and English as a second language [34]. These studies all found that the use of AR was at least equivalent to VR for the tested tasks.

While AR and VR have not been directly compared for spatial memory, two other types of spatial memory comparisons involving VR are relevant to our question. First, performance in VR has been compared extensively to real-world performance, demonstrating the potential for similar levels of accuracy and for transfer between training in one to the other - but also the limitations and gaps that remain [3], [35], [36]. From the neuroscience perspective, the extent to which the neural signals underlying behavioral performance are similar between virtual and real-world environments is currently debated, with some studies showing that signals are maintained while others finding significant differences [6], [37], [38].

Secondly, in recent years immersive VR setups that enable physical movement have become available. These include HMD setups with either natural walking in small safe environments, or on an omni-directional treadmill or simply stationary while allowing naturalistic head movements. The use of these setups has been compared to traditional screen-based desktop VR, showing general equivalence between the methods, with various advantages to walking over stationary conditions [3], [4], [39], [40], [41]. From the neuroscience perspective, it has been suggested that naturalistic head movements may be sufficient to elicit neural spatial signals in VR that might be missing in fully virtual paradigms [42]. Note however that these types of walking with an HMD, especially on a treadmill, may still hold considerable subjective differences to realistic real-world walking (e.g. [39], [43], [44]) and thus if performance is indeed improved by more natural physical walking then we would expect performance in AR to be between performance in immersive VR to performance in real-world paradigms.

Furthermore, while AR has the advantages of both real world and immersive VR, it is still in its current technological level a compromise between them. Although AR provides much more flexibility than regular real-world environments, it still does not match the flexibility of fully immersive VR as it continues to rely on the basic layout of the actual physical environment. The naturalistic feeling from using AR tends to break down in complex environments with occluding surfaces where sometimes the accuracy of the positioning of augmented objects can be problematic. In both of these cases, further advances in AR technology will continue to mitigate these differences to a great extent [45], [46], [47], [48], [49]. Thus, though AR tools are still new and evolving and we can expect improved results going forward, even current versions can already be utilized to create experiments that are more naturalistic and better capture human performance.

Thus, future work should directly test this condition, extending our work by performing a task similar to ours in matched environments between stationary VR, mobile VR and mobile AR to disentangle the relative effect of physical motion vs. reality modality.

Potential for Neuroscience Research. Following earlier advances, AR has the potential of being an extremely powerful tool for psychological and neuroscience research. An important first step, which we contribute to here, is in establishing clear behavioral baselines for performance in AR, to enable better extrapolation and generalization from the much larger existing VR research. Specifically, for the research of spatial memory, one can use current AR tools to test a range of questions in spatial memory research. For example, will we see differences between familiar and unfamiliar environments? How does memory performance in AR environments vary indoors versus outdoors? The greater ecological validity of AR can offer especially strong potential when combined with mobile neuroimaging (e.g. mobile fNIRS, mobile EEG) and invasive brain recording (e.g. the chronically implanted Neuropace [50] or the RC+S devices as used here [18]). This can enable us to create flexible, but highly controlled, paradigms in naturalistic real world settings, which might allow us to identify novel brain signals that have been previously missing from findings obtained from VR-based paradigms [6]. For this reason we focused here on tablet based AR rather than on head mounted displays or smart glasses, as this avoids clashes between the AR and neuroimaging equipment.

Potential for Rehabilitation. In addition to basic research, our findings of improved realism and enjoyment for AR-based walking paradigms suggest a potentially useful route for creating translational tools such as for rehabilitation. Current research approaches for spatial memory rehabilitation face similar kinds of challenges as spatial memory research, although often the magnitude of these problems is magnified by the need for the paradigms to be accessible to participants with memory impairments [2], [47]. Existing real-world navigation paradigms are often too cumbersome to run in the clinic, not to mention home, and virtual paradigms have not been successfully adopted (e.g. placing multiple obstacles in changing locations for a patient to walk around as they walk up and down a corridor). Existing VR tools on the other hand also suffer from challenges such as the disconnect between patients and their environment (including the clinical staff or helping family members) and the complexity of interfaces. Because AR connects the patient more with their physical surroundings and may be more convenient, intuitive, and enjoyable for individuals with spatial memory impairments, these methods may have special utility for working with these challenged patients—this is a view that has also been previously suggested by others for other rehabilitation realms (e.g. [46], [47], [51], [52]). Furthermore, beyond the advantages mentioned above regarding naturalness and flexibility, our findings show also that AR has the advantage of being easier to use. For all of these reasons, we see great potential in future use of AR for spatial memory rehabilitation and training, and more generally for the realm of rehabilitation in general.

Conclusion

Our main impact and novelty is in providing a quantitative measurement of the improvement in spatial memory accuracy that results from walking in the real world with augmented reality compared to a matched stationary task with virtual reality. Our finding that spatial memory encoding while physically walking was significantly easier, more immersive and more fun as compared to virtual walking, and most importantly that performance was significantly more accurate, demonstrates the importance of physical movement for spatial research and the potential of AR tools for spatial memory research and rehabilitation. Our patients demonstrate the potential for use of such systems with clinical populations as well. Our case study demonstrates that beyond behavior these effects may extend also to the underlying neural representations challenging us to integrate physical movement into neural experiments as well. These findings hold significant potential as a foundation for future spatial memory research and rehabilitation.

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