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Not all those who wander are lost: Spatial exploration patterns and their relationship to gender and spatial memory

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ABSTRACT

When humans and animals navigate through environments, they form spatial memories important for supporting subsequent recall of locations relative to their own position and orientation, as well as to other object locations in the environment. The goal of the current study was to examine whether individual differences in initial exploration of a large-scale novel environment relate to subsequent spatial memories. A majority of studies examining spatial memory formed in large-scale spaces have constrained encoding of the environment by leading participants on pre-determined paths, thereby limiting their free exploration. We allowed participants to freely explore a large-scale, virtual environment to locate a set of objects within. We then tested their ability to navigate back to those objects as well as their ability to point to them from one another. Based on previous work suggesting gender differences in navigation strategies and spatial anxiety, we predicted that males and females would show different patterns of initial exploration and that these exploration patterns would account for gender differences in measures of spatial memory. We found that females revisited previous locations more often and showed lower rates of spreading through an area. These measures of exploration partially accounted for gender differences in efficiency in navigation and pointing accuracy to remembered locations. The results demonstrate the importance of exploration in spatial memory and provide a new perspective on gender differences in spatial cognition.

1. Introduction

Spatial navigational abilities are fundamental to many everyday goals ranging from exploring a new city to finding a familiar friend's house. Strikingly, much of the previous work assessing spatial navigation and spatial memory has not examined how people encode spatial information in a large-scale environment and how encoding might subsequently influence spatial memories for that environment. Instead, most past research has either constrained exploratory movement during encoding by leading participants along pre-planned routes (e.g., Rossano & Moak, 1998; Sadalla & Montello, 1989; Silverman et al., 2000; Weisberg, Schinazi, Newcombe, Shipley, & Epstein, 2014), or has not quantified behavioral patterns exhibited during encoding to examine their effects on later spatial memory (e.g., Castelli, Corazzini, & Geminiani, 2008; Malinowski & Gillespie, 2001, but see Sutton, Buset, & Keller, 2014 for an investigation of free exploration effects in pilots compared to non-pilots). In the current paper, we quantify unconstrained human exploration patterns in a large-scale, virtual environment. We then test for hypothesized gender differences in these exploration patterns and whether individual differences in exploration patterns predict spatial memory for these environments. By relating these exploration measures at encoding to subsequent retrieval of spatial information, we hope to inform theories and mechanisms of spatial learning and memory.

There are clear individual differences in navigation proficiency and preference. For example, studies have examined individual differences in the way that people encode new routes in the context of forming generalizable cognitive maps, finding that some people are able to integrate routes learned separately into a unified spatial representation whereas others are not (Weisberg & Newcombe, 2016; Weisberg et al., 2014). Others have identified stable biases within individuals who show either place or response strategies when given the opportunity to choose between multiple paths after learning a route (Furman, Clements-Stephens, Marchette, & Shelton, 2014). However, individual differences in the patterns of exploration while navigating (particularly when exploration is active and unconstrained by routes) and their

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relationship to spatial knowledge acquisition remains largely unexplored in humans.

1.1. Differences in spatial memory with free exploration

Gender is a prominent individual difference variable in spatial memory and navigation, especially in the context of navigation in large-scale space. The dominant view is that males and females differ in navigational preferences and success, with a tendency for males to show an advantage in navigation performance (Astur, Ortiz, & Sutherland, 1998; Castelli et al., 2008; Moffat, Hampson, & Hatzipantelis, 1998, but see Coluccia & Louse, 2004). Females tend to rely more heavily on route-based navigation, which primarily involves remembering when or where to make a specific turn (e.g., turn right at the museum) and is considered to be inflexible when the desired route must be altered (Lawton, 1994). In contrast, males rely more heavily on survey-based navigation or orientation strategy, which primarily involves remembering or inferring metric information about the spatial configuration in a reference frame independent of the observer. Survey-based navigation is more flexible, allowing the navigator to take shortcuts or detours when necessary (Lawton, 1994). The self-reported gender differences in navigation strategy tend to parallel the gender differences observed in spatial memory, as males have been shown to outperform females when asked to point in the direction of a distant location or find their way back to previously visited locations (Castelli, et al., 2008; Gagnon, Cashdan, Stefanucci, & Creem-Regehr, 2016; Padilla, Creem-Regehr, Stefanucci, & Cashdan, 2017).

However, a review of much of the spatial cognition and navigation literature suggests that a male advantage in navigation tasks may not be so pervasive, given that only 58% of real and virtual world experiments found a significant male advantage in spatial orientation tasks (Coluccia & Louse, 2004). Their work also suggests that the male navigation advantage predominantly occurs (85% show the effect) when experiments involved a virtual world in which participants were allowed to actively control their movements. When the experimental task required "passive" exploration, only 28% of those experiments found a male advantage. For example, Rossano and Moak (1998) had participants either study a map or observe a video tour of a campus (i.e., passive spatial encoding), and found no difference between male and female performance on their spatial orientation or configuration test. Likewise, Sadalla and Montello (1989) asked participants to walk a path through a hallway with a variety of angled turns. Afterwards, participants estimated the angle of their turn and then pointed to their original direction of travel and their starting location. There was no difference between male and female performance. This experiment did involve active movement through the space, but participants were not allowed to freely explore, nor was there much to explore in the experimental environment.

In contrast, there is more evidence that free exploration tasks lead to gender differences in navigation. Malinowski and Gillespie (2001) asked 978 military personnel to explore a 6 km outdoor area for 10 targets using a map and compass. Males found more targets and took less time to complete the task than females, while females reported more anxiety about the task than males. Waller, Knapp, and Hunt (2001) allowed participants to freely explore virtual and real world mazes. Their main objective was to test the ability to transfer spatial knowledge from a virtual world to a real world, but they found that males pointed more accurately to landmarks than females in both environments. Using a large battery of tasks, Montello, Lovelace, Golledge, and Self (1999) found gender differences in tests of large-scale spatial knowledge when acquired from direct experience but no gender differences when learning novel spaces with maps. Silverman and Eals' (1992) hunter-gatherer theory of spatial gender differences also supports the notion that gender differences in navigation would be more apparent in unconstrained exploration contexts. Specifically, males' use of an orientation strategy that evolved to support large range size hunting and females' use of a landmark strategy that benefited local object location memory would predict differences in how unconstrained spaces are both explored and remembered.

Another well-known task that allows for free exploration and tends to show reliable gender differences in navigation performance is the Morris water maze, adapted for humans. In a typical water maze task, participants explore a small arena in search of a hidden platform. Exploration is only constrained by the size of the arena. After participants find the platform, they are repositioned at some other location within the arena and asked to navigate back to the platform. Males typically outperform females when assessing memory for the platform location, even though the task is usually completed in a relatively small space (Astur et al., 1998, see Padilla et al., 2017 for a large-scale task) and tend to show different strategies in navigating back to the target location (Rahman, Sharp, McVeigh & Ho, 2017).

The previously reviewed literature suggests that unconstrained exploration is an important factor related to gender differences in spatial memory. We set out to determine *how* exploration, when unconstrained, might differ among individuals. Preliminary evidence derived from self-reports suggests that aversion to risk and range size may predict strategies for navigation. Cashdan, Gagnon, Stefanucci, Butner, and Creem-Regehr (2018) assessed individuals' reports of sense of direction, wayfinding strategies, and wayfinding anxiety. Using structural equation modeling, they found that willingness to take risks predicted larger ranges, and males' greater propensity toward risk-taking mediated the gender difference in range size. However, range size was only a partial mediator of navigation strategy, with caution (desire to avoid harm and risk aversion) also affecting navigational strategy directly. This model is consistent with the empirical results found in Gagnon et al. (2016), which also showed that the desire to avoid harm was associated with increased caution in exploratory behavior in a desktop virtual environment navigation task. Gagnon et al. (2016) also found that these cautious exploratory behaviors completely explained gender differences in the efficiency of navigating back to previously discovered targets, but did not account for the gender difference in accuracy of pointing to remembered targets. In addition, recent work suggests that trait anxiety may interact with lower mental rotation ability in males to predict a reduction in map-based route learning (Schmitz, 1997; Thoresen et al., 2016). Thus, in the current study we are particularly interested in quantifying participants' caution in exploration in order to understand its potential relation to differences in strategy employed by males and females as well as subsequent spatial memory.

1.2. Measures of free exploration

In order to better understand the relationship between exploration patterns during encoding and later spatial memory for an environment, additional methods for quantifying *how* a space is explored are needed. Here, we used two methodologies to quantify exploration patterns to evaluate their relationship to spatial memory. There is a large body of research in behavioral ecology devoted to the study and quantification of animal movement and how it relates to achieving adaptive goals like foraging for food and finding mates (Turchin, 1998). Turchin's methods motivated our choice of measures. Specifically, our measures allow us to understand how dynamic patterns of exploration may relate to spatial memory. We ask whether participants *revisited* more locations (possibly indicating caution during exploration or a preference to return to known locations) and *diffused* through the space more quickly (thereby visiting more unique locations and experiencing the world from more perspectives). It is important to note that these two measures are not orthogonal. If navigators are more quickly diffusing through a space, then they have a lower likelihood of revisiting locations. While potentially opposite effects of cautious behavior, these measures also convey different information about exploration. For example, it would be possible to show lower rates of diffusion by simply not moving much, even without revisiting prior locations. We describe each of these measures in more detail in the following sections.

1.2.1. Exploration involving revisiting

Gagnon et al.'s (2016) findings suggest that females tend to exhibit more cautious behavior during exploration, consistent with self-report measures of greater wayfinding anxiety in females (Lawton & Kallai, 2002). Therefore, we implemented the same analysis for assessing caution in exploration used in Gagnon et al. (2016), which measured the amount of *revisiting behavior* while exploring. We define revisiting as an instance of a person traveling back to a previously explored locale. Its operationalization and measurement will be described in more detail in the methods. We operationalized caution as revisiting because revisiting known locales reduces the risk of getting lost or hurt. Although our virtual environment task did not include the possibility of actual harm, we assume that established cautious patterns of exploration would more generally be revealed in virtual environment behavior as well. We hypothesized that females would exhibit more revisiting than males, because sticking to previously explored locales should reflect caution and risk-aversion when exploring a novel environment. We also predicted that more revisiting should be associated with worse subsequent spatial memory, because space would be explored less efficiently and extensively.

1.2.2. Exploration through diffusion

As a second approach to describing exploration, we applied a well-known measure of movement over time called diffusion (see Philibert, 2006 for a good review of this concept). Diffusion can be thought of as the rate that an entity (e.g., organisms or particles) spreads through an area. The term originates in physics, where it is used to understand the distribution of particles in a medium. For instance, Einstein (1905) discovered that the random movement of a particle diffuses at a rate proportional to the square root of time, known as normal diffusion. The consecutive movement of these particles is typically uncorrelated over time, and is known as Brownian motion or a random walk. This means that if an entity is not compelled to move in one particular direction, then it will undergo normal or subdiffusion. On the other hand, if an entity's movement is correlated and moves in a particular direction then its movement is superdiffusive, which results in a diffusion rate greater than the square root of time (Ben-Avraham & Havlin, 2000).

The use of diffusion is also widespread within the animal movement literature. The term Levy walk has been used to describe superdiffusive mobility patterns (Shlesinger, Klafter, & Wong, 1982), because the movement of an animal tends to be superdiffusive and thus more efficient in exploring a space (Rhee, et al., 2011; Benhamou, 2004; Vishwanathan, Raposo & Da Luz, 2008), possibly due to an animal's ability to remember where it had been and a desire to move away from its previous spatial locations (Fagan et al., 2013). Recently, Rhee et al. (2011) analyzed GPS tracks of individuals while on a campus, at a state fair, or an amusement park. One of their findings was that human mobility in these contexts was superdiffusive. Diffusion has been widespread in its use within the animal movement domain, but its use for understanding human spatial memory has not been explored in much depth. Thus, we hope to use diffusion to learn more about unconstrained human exploration in a novel virtual environment context. As a separate but related measure to revisiting, we expected that less cautious exploration behavior would be related to greater diffusion and that males would be more likely to exhibit superdiffusive patterns of exploration than females. We predicted that exploration patterns characterized with greater diffusion would predict better subsequent spatial memory because of the greater extent of space traveled over time.

1.3. Overview of current study

Participants freely explored a virtual, outdoor environment with the goal of locating three objects. They were given the objects in succession and were asked to search for each of them starting from a common (home) location. Once an object was found, participants were asked to return to the home location and then to navigate back to the target object again. This design allowed participants to take more efficient shortcuts back to the previously located target if they had developed enough knowledge of the environment to do so. When participants had successfully found all the targets and navigated back to them, they were asked to point to each of the targets from the home location, as well as

Fig. 1. Screenshots demonstrating the variety of visual appearance throughout the virtual environment. Images were captured from the first person camera used by participants during the experiment.

from the targets to each other. We instructed participants explicitly that they would be asked to remember the locations because we were specifically interested in testing spatial knowledge acquisition rather than implicit spatial learning.

We hypothesized that exploration patterns that were less cautious and more diffusive over time and space would relate to less error in navigating directly back to the learned object and less error in remembering the location of those objects in the world. Further, we predicted that males would exhibit more efficient exploration patterns—less revisiting and greater diffusion—and better spatial memory, but that these more effective exploration patterns would mediate the oft-observed gender differences in spatial memory. The inclusion of two memory measures (navigation back to object and pointing to object locations) also allowed us to test whether these predicted effects of exploration would occur in two forms of memory retrieval.

2. Method

2.1. Participants

Undergraduate students at the University of Utah participated for course credit ($N = 106$; 60 Females, 46 Males; Mean Age = 21.7, $SD = 5.0$). All participants had normal or corrected-to-normal vision. Eight females and 2 males did not complete the experiment due to motion sickness, leaving 96 participants (52 Females, 44 Males) in our sample.

2.2. Materials

The virtual world was developed using Unity 4.6, and consisted of a 1 km^2 rectangular area containing several subregions: a desert, swamp, deciduous forest, coniferous forest, grassland, and meadows. Each subregion contained unique vegetation and geological features (see Fig. 1 for screenshots of the environment and Fig. 2 for a top-down map view of the layout of the subregions). There were two main geological features that were visible from nearly all locations in the world: a

Fig. 2. A map view of the virtual environment intended to show the relative layout of the sub-regions. Shapes are superimposed on the map in this image to indicate the home location (star) and the target objects (cart = pentagon, well = square, chest = circle).

sandstone canyon and a mountain peak. A waterfall, large boulders, and an arch were visible from approximately 0.5 km away. Uniquely colored trees, rocks, and hills were visible within a subregion, and then unique bushes and ground cover (i.e., flowers, grass) were visible from only certain locations within a subregion. A large lake bordered one of the four sides of the virtual world, a river separated the coniferous forest from the rest of the subregions, and a small pond was located between the meadow and the swamp. Finally, a square white platform indicated the participant's starting or home location, while a wooden cart, a treasure chest, and a water well represented the target objects. On the first exploration trial, one of the objects was present in the world along with the start location. After an object was found, then it would remain in the world during exploration to the next object, but other objects were not present until searched for or located. The starting location and the location of the target objects were identical for all participants. Participants viewed the world from a first-person perspective (a virtual eye height of 1.8 m) and controlled their movement using an Xbox 360 wired controller (maximum walking speed was 15 m/s and maximum turning speed was 150°/s). The virtual world was displayed on a 60 cm monitor (resolution: 1920 × 1200, rendered horizontal field of view: 60°).

The following questionnaires were administered online via Survey Monkey as part of a larger project: 15-item Santa Barbara Sense of Direction (SBSOD; Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006), the Navigation Strategy Scale and Spatial Anxiety Scale (Lawton & Kallai, 2002), the 26-item Harm Avoidance subscale from the Multidimensional Personality Questionnaire (Tellegen & Waller, 2008), and a 79-item list of local, national, and worldwide locations and regions to assess range size. Only the survey knowledge and spatial anxiety questions from the Lawton and Kallai (2002) scale were used in the current study.

2.3. Procedure

Participants were seated at a computer in a quiet room. After finishing the consent process, the experimenter relayed the following instructions:

> *In this experiment you will be in a virtual world, similar to a first-person video game.*
> *When you begin the task, you will see a white platform with an object hovering over it.*
> *This is your starting location, and the hovering object is your first target object. As soon as you press "A" on the controller, this object will be hidden somewhere in the world, and your task is to find it as quickly as possible. After you find the object, you will be asked to navigate back to the starting platform as quickly as possible. From there you will be asked to navigate back to the object as quickly as possible. The object will be located in the same location you originally found it, so do your best to remember its location when you first find it. Once you navigate back to the object, you'll turn around and go back to the starting location and begin the next trial. From here, a new object will appear hovering over the starting platform. As soon as you press "A" on the controller, this object will then be hidden somewhere in the world, and you will repeat the entire process for this object, and then for the final object. Once you've finished exploring and navigating you will be at the starting location and asked to point, one at a time, in the direction you would travel if you were to return to each object. To do this, you will move the cross-hair on the screen such that it is pointing in the direction you would travel if you were to return to each object. Then, you will be teleported to an object and asked to point in the direction of the starting platform as well as the other two objects. You will repeat this process for all three objects. Finally, instructions will be provided at the bottom of the screen, guiding you through the entire procedure.*

The experimenter then explained how to use the controller, and informed the participant that there was an online survey to take after they finished. Participants were informed that if they began to feel sick, the experiment would be terminated and they would receive their full participation credit.

Participants were also administered the online questionnaires listed in the materials section after completing the virtual exploration task. Finally, we recorded the participant's video gaming experience, and the purpose of the study was revealed to them at this time.

2.4. Data processing

We recorded the location (X, Y, and Z) and the camera orientation of the participant over the course of the entire virtual exploration and navigation task. The memory test trials were not included in any of the three analyses of exploration. These data were originally sampled at 20 Hz, but were then down-sampled to 1 Hz prior to performing any other processing or analysis. Next, we trimmed the beginning and end of each trajectory (i.e., 3 exploration bouts, and the 9 navigation bouts), such that they began and ended when the participant was 15 m away from their starting location and destination (i.e., starting platform or target object). We chose to trim the data as such for two important reasons. First, at the very beginning of the experiment, some participants were confused about the task instructions, so they did not move for a period of time, while the experimenter clarified the instructions for them. We did not want these data to skew the results of our exploration analysis given they did not reflect exploration. Second, once participants found the target object or navigated back to it, they were required to record this with a button press, but many participants were not able to do this successfully on their first attempt. As such, some participants wandered around the object attempting to successfully record that they had completed this portion of the experiment. We did not want this behavior to be considered in our calculations of caution or navigation performance, so it was removed. Finally, if participants were unable to find a target after 20 min, they were given a hint. Therefore, we only analyzed the first 20 min of the exploration data for every participant, as any data after this point do not reflect the participant's unbiased behavior.

2.4.1. Revisiting behavior

To evaluate cautious exploration, we calculated the extent to which the participants revisited locations throughout their trajectory. We projected a circle with a radius of 100 m around each individual point of the participant's trajectory within an exploration bout. We chose 100 m because it was roughly the distance at which the target objects were visible, though the environment was cluttered so they were not always visible from 100 m in every direction. After the trajectory exited the circle, any subsequent point found within the circle was considered an instance of revisiting (see Supplementary materials for R code of data analysis). We operationalized cautious exploration as revisiting because, whether one is avoiding getting lost or hurt, a locale previously occupied is safer than a new locale. However, there are other reasons why an individual may revisit a location that we cannot rule out. For example, retracing one's steps may aid in establishing a navigation route for later use or revisiting may occur if a person struggles to keep track of where they have been, especially while searching for objects.

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.cognition.2018.06.020. The data are also available for public use at the Open Science Framework: osf.io/f6jwn.

2.4.2. Diffusion

We used the diffusion coefficient of mean squared displacement to quantify diffusion, or the rate that the space was explored. The diffusion coefficient is a popular method used to measure the rate of diffusion of particles (Einstein, 1905). The rate at which participants diffuse into the space should reflect the distance they are willing to travel from a familiar location during exploration. If they are cautious, then this may result in less diffusion. To calculate the diffusion coefficient, we squared each displacement (i.e., changes in position) that occurred within a series of time lags (τ). Then, we took the mean displacement of each τ. We repeated this process for 4 separate τ, which were calculated by dividing the length of the time series (N) by 1, 2, 3, and 4 (τ = N/1…4). Thus, for instance, for a time series of $N = 1000$, the time lags would be $\tau_1 = 1000$, $\tau_2 = 500$, $\tau_3 = 333.33$, $\tau_4 = 250$ (see Rhee et al., 2011). Each displacement within a given time lag would be squared and the mean would be calculated for each time lag. Finally, we regressed mean-squared displacement on to time lag with a least-squares regression, where the slope is equal to the diffusion coefficient. The diffusion coefficient values were obtained for each individual three times, once from each of their three exploration trajectories (see Supplementary materials for R code of data analysis).

2.4.3. Navigation error

To measure subsequent navigation to remembered locations, we compared the trajectory traveled by participants when navigating back to each object to a straight line connecting the starting platform and the target object. We quantified the deviation of the navigation trajectory from a straight line using Fréchet distance. The Fréchet distance is a measure of the similarity of two curves that determines the minimum line length required to connect two units as they move along each curve. This is a widely used measure for computing both dynamic and static distances (Alt & Godau, 1995; Eiter & Mannila, 1994). Compared to a measure such as % difference in length between two paths, the Fréchet distance gives more information about the distributional properties of the traveled path and is a useful analysis for quantifying differences in paths that cross over each other, as is the case with navigation paths (see also Gagnon et al., 2016). Lower Fréchet distance estimates indicate more similarity between the navigation trajectory and a straight line to the target, interpreted as a more direct path or lower error.

2.4.4. Pointing error

Participants also made pointing responses to remembered object locations (three at each target location and three at the starting location) for a total of 12 responses. While located at the starting location, participants were asked to point in the direction of the three object locations by positioning a cross-hair using the Xbox controller, assessing their spatial knowledge for a relationship with which they had much experience (i.e., navigating to and from each target object). Similarly, while located at each object location, participants were asked to point the cross-hair to the starting location as one of their three pointing responses. In contrast, while located at each target object, participants were asked to point to the other two target objects. These pointing responses assess the participant's knowledge for spatial relationships they did not have experience with, because they never had to navigate between target objects.

3. Results

3.1. Are exploration and memory measures influenced by trial and gender?

We predicted that experience across multiple trials would likely affect both exploration and learning, so we first ran 2 (gender) × 3 (trial) ANOVAs on each of the two exploration measures to test for potential trial effects. For revisiting, there was a significant main effect of exploration trial, $F(2, 188) = 11.71$, $p < 0.001$, $\eta^2_p = 0.11$. Bonferroni-corrected, post hoc t-tests showed that Trial 1 ($M = 3.99$) did not significantly differ from Trial 2 ($M = 3.55$) ($p = 1.00$), but Trial 3 ($M = 1.94$) was significantly less than both Trials 1 and 2 (both $p < 0.001$), see Fig. 3. There was also a significant main effect of gender, $F(1, 94) = 9.55$, $p = 0.003$, $\eta^2_p = 0.09$, with females ($M = 3.88$) showing a higher rate of revisiting behavior on average

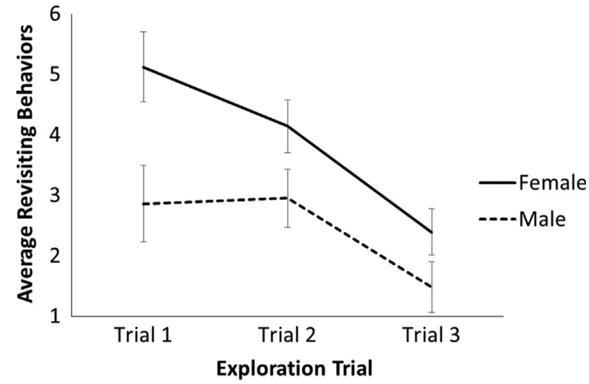

Fig. 3. Average revisiting behavior as a function of trial and gender. Error bars represent between-subjects standard errors of the mean.

than males ($M = 2.43$) across the three exploration trials. The trial × gender interaction was not significant, $F(2, 188) = 1.28$, $p = 0.279$, $\eta^2_p = 0.013$ (see Fig. 3).

For the diffusion coefficient, there was a significant main effect of exploration trial, $F(2, 188) = 16.41$, $p < 0.001$, $\eta^2_p = 0.15$. Bonferroni-corrected, post-hoc t-tests showed that Trial 1 ($M = 1.55\,m^2$) did not significantly differ from Trial 2 ($M = 1.54\,m^2$) ($p = 1.00$), but Trial 3 ($M = 1.67\,m^2$) was significantly greater than both Trials 1 and 2 (both $p > 0.001$). The main effect of gender did not reach significance, $F(1, 94) = 3.03$, $p = 0.085$, $\eta^2_p = 0.03$, with similar diffusion coefficient for males ($M = 1.61\,m^2$) and females ($M = 1.57\,m^2$). There was no gender × exploration trial interaction, $F(2, 188) = 0.78$, $p = 0.459$, $\eta^2_p = 0.01$, see Fig. 4.

We also tested navigation error for effects of gender and trial with 2 (gender) × 3 (trial) ANOVAs run on navigation error as quantified by Fréchet distance (separately for paths from start to object and object to start). When navigating from each object to the start, there was a significant main effect of trial, $F(2, 188) = 13.67$, $p < 0.001$, $\eta^2_p = 0.13$. A series of Bonferroni-corrected, post hoc t-tests revealed that Trial 1 ($M = 244.85$ m) significantly differed from both Trial 2 ($M = 95.94$ m) and Trial 3 ($M = 118.19$ m) (both $ps < 0.002$). Trial 2 did not significantly differ from Trial 3 ($p = 1.00$). There was also a significant main effect of gender, $F(1, 94) = 17.38$, $p < 0.001$, $\eta^2_p = 0.16$, with males ($M = 92.49$ m) performing better than females ($M = 204.18$ m). The gender × trial interaction did not reach significance $F(2, 188) = 2.84$, $p = 0.060$, $\eta^2_p = 0.03$ (see top panel of Fig. 5).

When navigating from the start to each object, the pattern of results was identical to those above. There was a significant main effect of trial, $F(2, 188) = 23.68$, $p < 0.001$, $\eta^2_p = 0.20$. A series of Bonferroni-corrected, post hoc t-tests revealed that Trial 1 ($M = 294.98$ m)

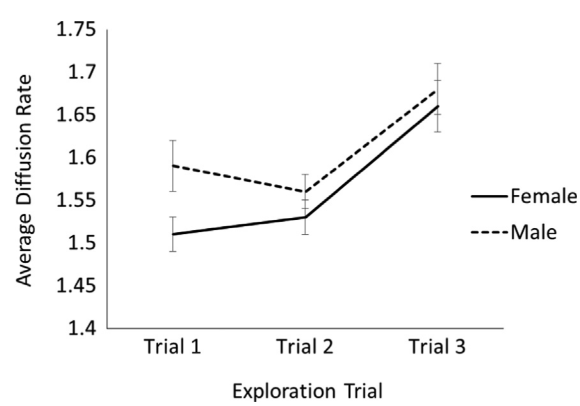

Fig. 4. Average diffusion coefficient characterizing diffusion rate as a function of trial and gender. Error bars represent between-subjects standard errors of the mean.

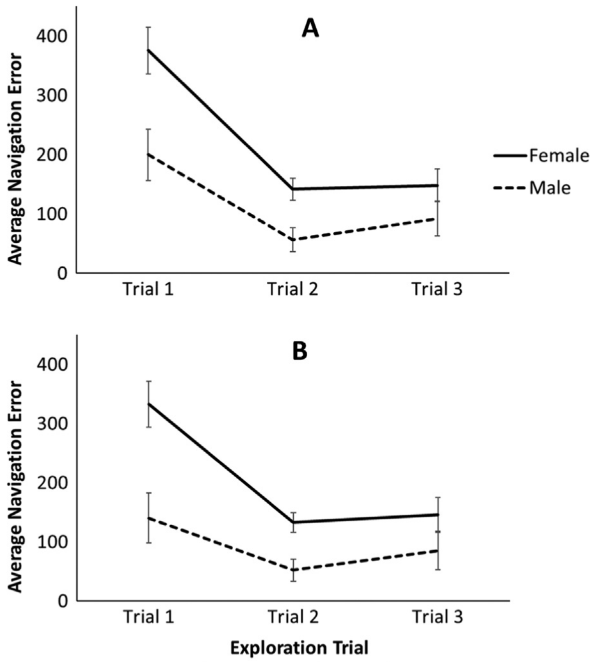

Fig. 5. Average navigation error (smaller Fréchet distance means greater efficiency) by trial and gender when navigating from the found object back to start (Panel A) and when navigating from start back to the found object (Panel B). Error bars represent between-subjects standard errors of the mean.

significantly differed from both Trial 2 ($M = 102.78$ m) and Trial 3 ($M = 122.69$ m) (both $ps < 0.001$). Trial 2 did not significantly differ from Trial 3 ($p = 1.00$). There was also a significant main effect of gender, $F(1, 94) = 15.29$, $p < 0.001$, $\eta^2_p = 0.14$, with males ($M = 116.25$ m) outperforming females ($M = 221.91$ m). The participant gender × exploration trial interaction was not significant $F(2, 188) = 2.16$, $p = 0.188$, $\eta^2_p = 0.02$ (see bottom panel of Fig. 5).

Finally, for the pointing error, we examined whether there were gender differences in error as a function of the type of pointing response (from start to object location, from object location to start, and from object to object) with a 2 (gender) × 3 (type: from start to object, from object to start, and from object to object) mixed model ANOVA, averaged across the three objects. There was a main effect of gender, $F(1, 94) = 4.77$, $p = 0.032$, $\eta^2_p = 0.05$, with greater pointing error for females ($M = 33°$) than males ($M = 26°$). There was also a main effect of type, $F(2, 188) = 16.21$, $p < 0.001$, $\eta^2_p = 0.15$. Bonferroni-corrected post-hoc *t*-tests found that pointing error from object to start ($M = 34°$) and from object to object ($M = 33°$) was significantly greater than error from start to object ($M = 22°$) ($p < 0.001$). Pointing error from object to start and object to object did not significantly differ ($p = 1.00$). The gender × type interaction was not significant, $F(2, 188) = 2.17$, $p = 0.118$, $\eta^2_p = 0.02$, see Fig. 6.

Thus, we found consistent gender differences across all of our measures, with greater revisiting and spatial memory error in females than males (with the exception of diffusion coefficient, which was marginally significantly different). However, we also found that there were consistent trial effects in the exploration variables. We expected this effect of trial given the greater degree of novelty associated with the environment in the first trial of the experiment. Thus, to test our second hypothesis, we used only the data from the first exploration trial.

3.2. *Do exploration patterns predict subsequent spatial memory?*

Our main goal was to assess how novel categorizations of participant exploration within a virtual environment relate to spatial memory

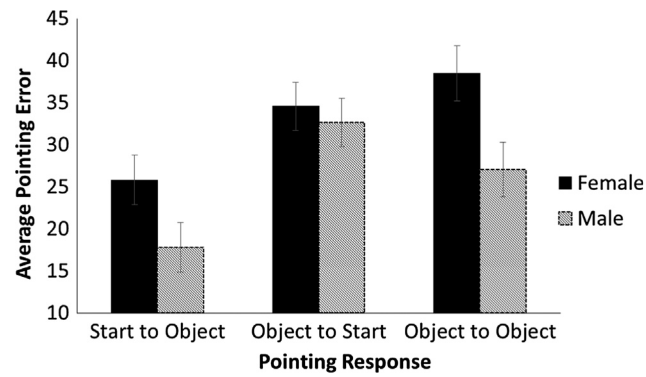

Fig. 6. Average pointing error for each pointing response type by gender. Error bars represent between-subjects standard errors of the mean.

for that environment, as measured by navigational error and pointing error to the previously visited targets. We predicted a male advantage in spatial memory, as supported by the analyses above, but also that diffusion and revisiting would mediate the relationship between gender and performance on the spatial memory measures. Utilizing structural equation modeling (SEM), two separate models – one for pointing error and one for navigation error – we tested the relationship between gender, diffusion, revisiting and each of the spatial memory outcomes. Again, given the strong effects of trial on both the exploration measures and the navigation error measure, we used only the first trial data in these models. For each participant, we averaged the first trial data for the two navigation directions and the three types of pointing responses and used these averages as the spatial memory outcomes in the models.

The models were of adequate fit (Hu & Bentler, 1999), with a $CFI = 0.91$ and $SRMR = 0.08$ and a $CFI = 0.90$ and $SRMR = 0.08$, for pointing error and navigation error outcomes, respectively. The Chi Square tests were significant, χ^2 (1) = 4.32, $p = 0.04$, χ^2 (1) = 4.27, $p = 0.04$. All parameter estimates are shown in Table 1 and Fig. 7 shows the full SEM path models.

For the model with pointing error as the outcome, gender significantly predicted diffusion coefficient and revisiting. The unstandardized indirect coefficients indicate whether the exploration measures mediate the effects of gender on pointing error. The unstandardized indirect coefficient for the effect of gender through diffusion coefficient to the pointing error was −5.10, $p = 0.03$. The unstandardized indirect coefficient for the effect of gender through revisiting to the pointing error was 3.74, $p = 0.21$. This result partially supports the predicted mediation effect of the exploration variables on

Table 1
SEM path coefficients.

	Unstandardized Estimate	Std. Error	P-Value	R^2
Pointing error outcome				
Pointing Error on				0.29
Diffusion	−4.23	1.74	0.02	
Gender	−3.64	0.83	< 0.001	
Revisiting	3.50	3.10	0.26	
Revisiting on				0.31
Gender	−1.46	0.47	0.002	
Diffusion on				0.27
Gender	0.04	0.01	0.007	
Navigation error outcome				
Navigation Error on				0.36
Diffusion	−9.92	10.73	0.88	
Gender	−8.77	2.59	0.001	
Revisiting	10.90	4.33	0.001	
Revisiting on				0.31
Gender	−2.27	0.84	0.007	
Diffusion				0.20
Gender	0.07	0.03	0.030	

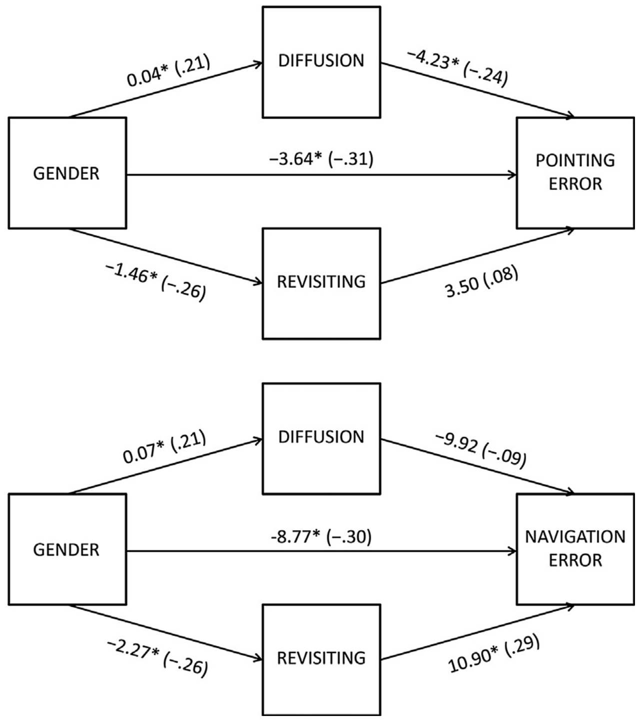

Fig. 7. Structural equation models testing the mediation effect of Diffusion and Revisiting on Pointing Error and Navigation Error. Direct unstandardized coefficients are depicted with standardized coefficients in parentheses, *$p < 0.05$. Gender is coded with Male = 1. Partial mediation of the gender effect through Diffusion to Pointing Error is supported by the unstandardized indirect coefficient (-5.10, $p = 0.03$). Partial mediation of the gender effect through Revisiting to Navigation Error is supported by the unstandardized indirect coefficient (-24.73, $p = 0.04$).

the relationship between gender and pointing error. As predicted, the diffusion coefficient was significantly related to pointing error, and partially mediated the relationship between gender and pointing error. Adopting an exploration pattern characterized by a greater rate of diffusion through space related to less pointing error. However, revisiting was not uniquely associated with pointing error (as revealed by the non-significant indirect coefficient), and thus did not further explain the effect of gender on pointing error.

For the model with navigation error as the outcome, gender significantly predicted the diffusion coefficient and revisiting. Testing for the mediation effect, the unstandardized indirect coefficient for the effect of gender through diffusion coefficient to the navigation error was -0.73, $p = 0.93$. The unstandardized indirect coefficient for the effect of gender through revisiting to the navigation error was -24.73, $p = 0.04$. This result partially supports the predicted mediation effect of the exploration variables on the relationship between gender and navigation error, but in a manner opposite of the pointing error model. Here, revisiting was significantly related to navigation error, and partially mediated the relationship between gender and navigation error. Adopting an exploration pattern with less revisiting related to less navigation error. However, the diffusion coefficient did not uniquely account for navigation error beyond the effect of gender.

3.3. Do self-report measures relate to exploration and memory measures?

We ran correlations between gender, first-trial exploration measures, first-trial navigation error, pointing error, and self-reported survey strategy, spatial anxiety, and video game experience (hours of play). Table 2 presents the results. We found support for gender differences in all of the self-reported variables in the expected directions, where males were higher on gaming hours and survey strategy and lower on spatial anxiety. Notably, gaming experience did not correlate with the exploration or spatial memory measures, suggesting that the differences in navigation are not likely a result of differences in familiarity or comfort with virtual environments. We also found that while survey strategy (e.g., orienting to global reference points) correlated with pointing and navigation error as would be predicted from previous spatial learning work in real and virtual environments, it did not correlate with the two exploration measures. In contrast, self-reported spatial anxiety did relate to both of the exploration measures, providing support for the notion that exploration patterns characterized by revisiting and diffusion are possibly related to differences in cautious behavior. We discuss these relationships further in Section 4.

4. Discussion

Our goal in this study was to test whether patterns of unconstrained exploration could provide an explanation for previously observed gender differences in spatial memory. We predicted that when placed in a novel environment with unconstrained exploration, (1) males and females would explore differently and (2) these differences in exploration would at least partially account for the expected gender differences in spatial memory. We predicted that males would explore greater amounts of space over time and with less caution than females, and that these characteristics of exploration patterns would lead to better spatial knowledge. We found support for our first hypothesis by showing that across all trials males explored a novel environment with less revisiting behavior than females. Likewise, we found that males had less navigation error, regardless of whether they were navigating from the start to the object or from the object back to the start. Males also had less pointing error, regardless of whether they pointed from the start, from the object, or between objects. In support of our second question, we tested the influence of exploration on gender differences in

Table 2
Correlations between gender, exploration measures, spatial memory measures, and self-report measures.

Variables	1	2	3	4	5	6	7	8
1. Gender	–							
2. Pointing error	−0.22*	–						
3. Navigation error	−0.35**	0.41**	–					
4. Revisiting	−0.27**	0.39**	0.29**	–				
5. Diffusion	0.22*	−0.20	−0.25*	−0.73**	–			
6. Gaming hours	0.20*	−0.08	−0.15	−0.08	−0.03	–		
7. Survey strategy	0.31**	−0.32**	0.30**	−0.17	0.14	0.04	–	
8. Spatial anxiety	−0.26*	0.28**	0.36**	0.34**	−0.26*	0.05	−0.35**	–

Note. Gender is coded such that female = 0 and male = 1. Greater survey strategy values are related to more reliance on a survey-based (orientation) strategy, orienting to global reference points such as cardinal directions or distal (far) cues. Greater spatial anxiety values are related to higher anxiety about wayfinding and sense of direction tasks.

* $p < 0.05$.

** $p < 0.01$, two-tailed.

spatial memory for first trial navigation with a mediation model. We found that gender differences in spatial memory were mediated by exploration patterns, but that the two exploration measures related differently to the two spatial memory measures. The rate of diffusion partially accounted for the effect of gender on pointing error, and the level of revisiting contributed to the effect of gender on navigation error. Higher rates of diffusion predicted better pointing to remembered targets and lower amounts of revisiting produced more direct navigation to these targets.

Our current results clearly demonstrate gender differences in unconstrained exploration of a large-scale virtual environment. Gagnon et al. (2016) were the first to establish that females showed greater caution during exploration of a virtual environment as quantified by the measure of revisiting. We replicated this effect in a larger and more complex virtual environment. We developed a second quantitative measure of dynamic exploration based on previous work with non-human animal and human populations that has identified super-diffusive patterns of locomotion as those that move in a particular direction (with steps that are correlated across time) and allow for more efficient spatial exploration. We predicted that males would show more superdiffusion—also predicted to be related to less cautious exploration behavior—and tested whether this would result in better memory for target locations. We found the predicted gender difference; males diffused through the space at a faster rate on their first exploration trial. Further, we found that this exploration pattern did explain some of the male advantage seen in spatial memory, as revealed through pointing error.

While we generally found support for exploration patterns contributing to spatial memory beyond a gender-differentiated effect, our models revealed that there was a somewhat different relationship between the two exploration measures and the two memory measures. For navigation error, revisiting had a stronger effect than the quantification of diffusion. This finding also replicates Gagnon et al. (2016) who found that revisiting entirely mediated the effect of gender on navigation error but did not explain gender differences in pointing error. In our current study, the additional measurement of diffusion shows that a different characterization of exploration partially explains the gender difference in pointing error. The difference in effects between exploration measures and spatial memory measures bring up important points related to decisions about measurement. First, for measuring exploration, it is clear that there are numerous ways to quantify how a space is explored. We chose to use two measures that captured the dynamic search process of observers and were motivated by previous findings related to cautious behavior. However, even though these measures are theoretically related in motivation, exploration is characterized differently with each of them. Diffusion defines a pattern of movement through space that allows navigators to amass multiple perspectives on the environment as superdiffusion increases. This exposure to multiple perspectives could reasonably provide the information needed for object-to-object spatial representations (like those that were tested at the end of the learning trials in our experiment), but may not have been explicitly experienced during travel. Previous research suggests that when people receive many different views of a space, their layout knowledge is more accurate (Evans & Pezdek, 1980; Thorndyke & Hayes-Roth, 1982). In contrast, the amount of revisiting is directly tied to how much time is spent in a given location and perhaps increased time at one specific location would limit understanding of the most direct path from the start back to the learned locations. While our methodologies and results provide a start to conceptualizing what could or should be measured in exploration as it relates to spatial memory, there is much room for future work in this direction.

The use of two dependent measures of spatial memory also provides a contribution on its own that could inform investigators' decisions about how to measure memory of large-scale spaces. Pointing measures are often used in the real world due to the practicalities of measurement (Hegarty, et al., 2006; Montello, Richardson, Hegarty & Provenza, 1999; Shelton & McNamara, 1997). These pointing measures have been extended to virtual world tasks as well (Weisberg et al., 2014, Weisberg & Newcombe, 2016). In the current study, we assessed the utility of the traditional pointing measure as well as a less-used measure of efficiency of navigation to remembered targets (navigation error). The two tasks differ in terms of timescale and frames of reference used. The pointing task was performed after all of the exploration trials and from a static location (start or target location). Nonetheless, we found consistent gender differences across these two measures showing more accurate performance in males. Performance on the pointing measure correlated with navigation error, which may be considered a more ecologically valid measure of survey-knowledge in that it assesses the ability to take a direct path to a learned target. This correlation can inform and validate decisions about choices of response measures in related task contexts.

The correlations between self-reported experience and abilities, exploration measures, and memory measures provide additional insights into the role of exploration on spatial memory. Higher self-reported survey strategy predicted decreased pointing error and navigation error as we would expect from prior work on wayfinding tasks (e.g., Castelli et al., 2008; Hegarty et al., 2006; Lawton, Charleston, & Zieles, 1996; Pazzaglia & De Beni, 2001). However, it did not significantly correlate with either of the exploration measures (diffusion coefficient or revisiting). This non-significant correlation is surprising, but it suggests that survey strategy and exploration may have independent contributions to spatial memory across individuals and helps to explain the partial (but not full) mediation of gender on spatial memory that was found. Further, the fact that survey strategy was self-reported and exploration was measured behaviorally shows that objective indices may have additional explanatory power for understanding gender differences in spatial memory. In contrast to survey strategy, self-reported spatial anxiety did relate to both of the exploration measures in the directions we would expect, which corroborates our and others' claim (Gagnon et al., 2016) that females show more cautious behavior (i.e., more revisiting and less diffusion) when allowed to explore unconstrained. Although we found a correlation between gender and video gaming hours (with males playing more than females), the lack of correlation between video game experience and any of the measures of exploration or spatial memory suggests that such prior experience and familiarity with video games or joysticks did not affect exploration or performance in the virtual task.

There are some methodological limitations that may have influenced our findings. First, we used a virtual environment because this would ensure that the environment was novel and consistent across participants. In relation to our hypothesis, which involved gender differences in exploration, our virtual environment did not contain any costs (i.e., dangers) or benefits. Certainly, we do not believe that female participants explored with caution because they were avoiding physical harm or that males explored the environment to incur any benefits unrelated to the task. However, we do believe that people likely establish a way of exploring a novel environment, which then carries over to virtual environments as well. Future work may consider including costs and benefits in a virtual environment navigation task, such as the metabolic costs of travel. Also, navigation is a multi-sensory process (Chrastil & Warren, 2012; Sholl, 1989) and our virtual environment almost exclusively relied on visual information for navigation. Chrastil and Warren (2013) found that information from physical walking through an environment improved spatial learning. It may be the case that gender differences are only found in navigation tasks that require individuals to rely solely on visual information. However, Malinowski and Gillespie (2001) did find a male navigation advantage in a large-scale, real-world setting where all sensory cues were available for use while navigating (see also, Silverman et al., 2000) and a convincing body of work continues to develop that demonstrates the validity of studying individual differences in both behavioral and neural outcomes using virtual visual navigation methods (e.g., Furman, et al., 2014, Harris & Wolbers, 2014, Weisberg et al., 2014). Our current results add to this literature by highlighting the importance of exploration patterns for subsequent memory within a novel and large-scale environment. These findings support the view that navigational style depends on the way one uses information both during encoding and retrieval (Furman et al., 2014) and that individual differences in navigation success may be best characterized by multiple experiential factors including active experience with the initially learned environment.

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