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Sex Differences in Exploration Behavior and the Relationship to Harm Avoidance

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Abstract Venturing into novel terrain poses physical risks to a female and her offspring. Females have a greater tendency to avoid physical harm, while males tend to have larger range sizes and often outperform females in navigation-related tasks. Given this backdrop, we expected that females would explore a novel environment with more caution than males, and that more-cautious exploration would negatively affect navigation performance. Participants explored a novel, large-scale, virtual environment in search of five objects, pointed in the direction of each object from the origin, and then navigated back to the objects. We found that females demonstrated more caution while exploring as reflected in the increased amounts of pausing and revisiting of previously traversed locations. In addition, more pausing and revisiting behaviors led to degradation in navigation performance. Finally, individual levels of trait harm avoidance were positively associated with the amount of revisiting behavior during exploration. These findings support the idea that the fitness costs associated with long-distance travel may encourage females to take a more cautious approach to spatial exploration, and that this caution may partially explain the sex differences in navigation performance.

Keywords Sex differences · Exploration · Navigation · Harm avoidance

Exploring new locales can bring rich rewards but can also expose the traveler to danger. Those risks and rewards are likely to fall on men and women differently, with consequences for both travel distances and exploration. Most of the

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evolutionary literature on this topic has addressed the potential fitness benefits that accrue to males from larger ranges. But greater fitness costs to females of long-distance travel are likely to play an equally large role, and to shape not only range size but the ways in which men and women explore novel spaces and learn spatially from that exploration. In this study, we allow women and men to explore a large virtual outdoor space in order to see whether women have a more cautious style of exploration than men do, and whether this is related to their ability to navigate back to remembered locations in the space. Little is known about how women and men explore a novel environment, yet different patterns of movement are likely to yield different types of spatial information and thereby affect a traveler's ability to remember spatial relationships that would aid in navigation. Although sex differences in exploration have not been studied directly, our hypotheses are motivated by well-established sex differences in mobility, spatial anxiety, and harm avoidance. We begin, therefore, by discussing each of these and how they are likely to affect exploration strategies in men and women.

A sex difference in mobility, with males doing more long-distance travel than females, is widely reported in both Western (Ecuyer-Dab and Robert 2004; Hart 1979; Matthews 1987) and small-scale non-Western (MacDonald and Hewlett 1999; Miner et al. 2014; Munroe and Munroe 1971; Vashro and Cashdan 2015; Whiting and Edwards 1992) populations. Although there are various proximate motives for travel, some evidence indicates that larger ranges may confer reproductive benefits on men (MacDonald and Hewlett 1999; Miner et al. 2014; Vashro and Cashdan 2015), as they do for some other polygynous species (Gaulin and Fitzgerald 1989; Jasarevic et al. 2012). We might expect, therefore, that the greater benefits of large ranges would select for a greater motivation among males to explore novel areas and cover more ground while doing so.

Another reason to expect sex differences in spatial exploration lies in women's greater concern about physical harm. Travel, particularly over large distances and novel terrain, carries risks, and a woman lost or injured in travel would suffer a greater fitness cost than her mate because of her greater parental investment: children are less likely to survive the death of a mother than a father (Sear and Mace 2008). She may also face greater direct costs arising from the risk of rape and assault, and (in subsistence economies) from the constraints on mobility of traveling with an infant on her back.

Female psychology reflects these fitness costs: women report greater wayfinding anxiety than men (Devlin and Bernstein 1995; Lawton 1994; Lawton and Kallai 2002; Picucci et al. 2011; Schmitz 1997) and are more harm-avoidant and risk-averse generally (Campbell 1999). Women are more prone to phobias that reflect physical dangers (Marks 1987), whereas males are more likely to seek out risky activities (Croson and Gneezy 2009; Cross et al. 2013). A meta-analysis of 150 studies (Byrnes et al. 1999) found that males were more likely to take risks in nearly all contexts, with a small effect size overall (d=0.13) but with larger differences in some areas, including physical risks (d=0.43). Women are less likely to take risks, in part, because they perceive the potential negative outcomes to be greater (Harris et al. 2006). Schmitz (1997) found that children who were more anxious and fearful navigated through a real-world maze more slowly. Psychological differences in harm avoidance and risk aversion should also be reflected in a more cautious style of *unconstrained* spatial exploration. Our primary hypothesis, therefore, is that women will tend to exhibit greater caution when exploring novel spaces. We investigated this in a large virtual outdoor environment by asking participants to venture forth in search of five different objects. After finding the objects and returning to the starting point, they were asked to point to each object from the starting point and then return to the locations using as direct a path as possible. We analyzed their exploration tracks for two behaviors that might reflect greater caution in exploration: pausing and revisiting. Pausing might indicate the need for additional cues, desire to check previously viewed terrain, or general discomfort about forging ahead; a person who is unafraid of taking a wrong turn is likely to keep moving and to stop less frequently. Another pattern that might reflect caution in exploration is when a person thoroughly explores one area before moving to a novel area. That area might then become a known base from which the person feels more comfortable exploring, and to which she can return if necessary. We are calling this type of behavior "revisiting" because we identify it by a path that returns to (revisits) a recently traversed location before moving on. To provide further support our choice of pausing and revisiting as indicators of cautious travel, we collected questionnaire data on harm avoidance to see whether more harm-avoidant individuals did more pausing and revisiting.

A cautious style of exploration might also affect the distance traveled before stopping or turning. A growing body of evidence suggests that the movement patterns of a variety of species can be described by a Lévy walk pattern, which consists of a large number of small moves (i.e., "steps") linked by a small number of long-distance moves (Bartumeus 2007; Boyer et al. 2006; Raichlen et al. 2014). The length of a "step" is defined as the distance traveled before pausing or making a significant change in heading (e.g., turning more than 40°) (Raichlen et al. 2014). We hypothesized that if women explore more cautiously than men, showing more revisiting and pausing behaviors, then women should also show a higher proportion of small step lengths than men.

Our second hypothesis concerns the effect of exploration patterns on spatial memory. Previous research demonstrates that males often outperform females in a wide range of navigation and spatial memory tasks (Astur et al. 2004; Moffat et al. 1998; Montello et al. 1999; Schmitz 1999). In a more nuanced view, when participants are allowed to control their movement during the navigation task, approximately 86% of studies show a male navigation advantage. In contrast, when participants do not actively control their movement during the task, only 29% of studies show a male navigation advantage (Coluccia and Louse 2004), suggesting that how males and females move around in an environment contributes to sex differences in navigation performance. Generally speaking, exposure to a novel environment provides a wealth of knowledge that can be used to develop a "mental map." Therefore, we expect that how one explores a novel environment influences the quality of spatial memory for that space. In particular, we expect that more revisiting and pausing behaviors, and a lower proportion of long step lengths, will lead to more navigation inefficiency (i.e., not taking a direct path back to a previously discovered location) and greater errors in an explicit spatial memory task.

Methods

Materials

Virtual World and Setup The virtual world was developed using Unity (4.6.0) (2014), and consisted of a 1 km^2 rectangular world with a variety of hills, rocks, trees, and other vegetation (see Fig. 1 for examples). Two large landmarks, a waterfall and a mountain, were visible from almost every position within the world. Five objects (a well, straw hut, shed, large white cube, and large white sphere) and a starting location (large white pillar) were located throughout the virtual world such that none of the objects were visible from any of the other objects (see Fig. 2 for layout of objects). Participants moved through the world from a first-person perspective (a virtual eye height of 1.8 m and a walking speed of 10 m/s) using an Xbox 360 wired controller. The X, Y, Z position and camera orientation of the virtual camera was recorded at a sampling rate of 10 Hz. For each of the five objects and the starting location, a picture was taken from the virtual first-person camera such that the surrounding environment was not pictured. Each picture was labelled with the object name and provided to participants throughout the experiment so they knew the visual appearance of each object. The virtual world was displayed on a 68.58 cm Apple display (resolution: 2560 × 1440, viewing angle: 178° × 178°, rendered horizontal field of view: 60°).

Harm-Avoidance Questionnaire The 26-item forced-choice Harm Avoidance subscale from the Multidimensional Personality Questionnaire (MPQ) (Tellegen

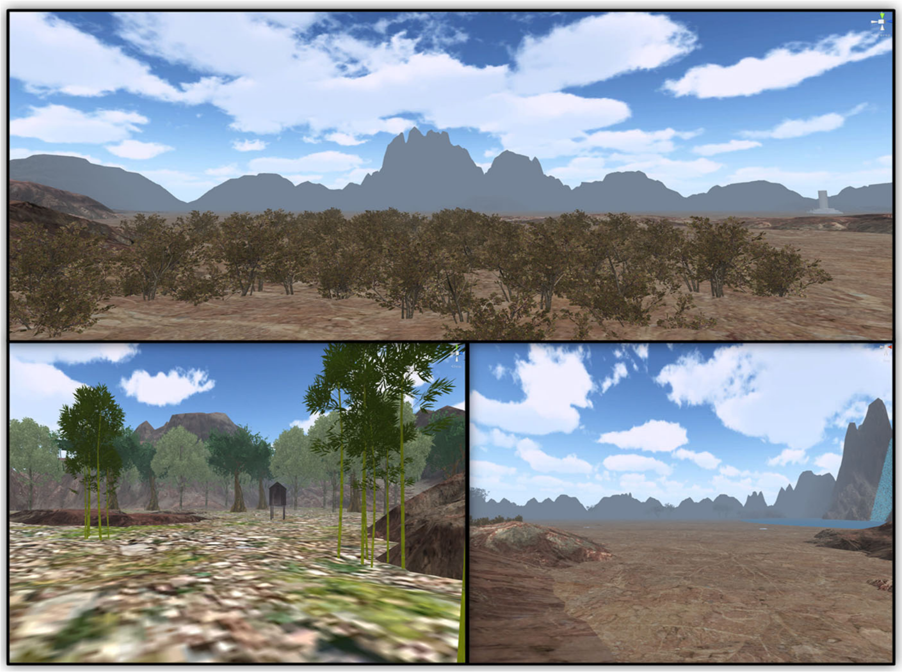

Fig. 1 Three first-person-perspective screenshots of the virtual world

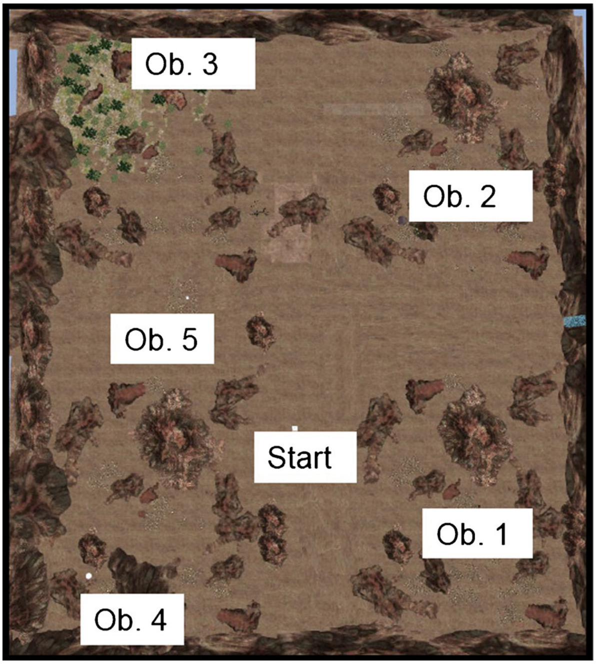

Fig. 2 Top-down view depicting the layout of the objects and the starting location within the virtual world (approximately 1×1 km)

and Waller 2008) was administered online using Survey Monkey (www.surveymonkey.com).

The participants were asked to choose one of two activities, where one has the potential of physical harm. The percent of safe options chosen is our measure of harm avoidance.

Participants

Seventy-eight undergraduates (36 female, 42 male; *M* age=22.6 years) with normal or corrected-to-normal vision participated in the experiment for course credit or monetary compensation. All participants provided written informed consent. The self-report measures were not initially included, so only 46 (20 females, 26 males) participants completed both the exploration task and the self-report measures.

Procedure

After participants read and signed the informed consent, they were seated at a computer in a quiet room. The experimenter explained that they would be in a virtual world similar to a first-person video game, and that their task was to search for five objects as quickly as possible (to be found in any order). Once all five objects were found, they would then navigate back to the starting location, at which time the program would ask them to point in the direction of each of the five objects one at a time using a cross-hair displayed on the screen. They would then navigate back to each of the five objects in any order they chose, return to the starting location, and point again in the direction of each object one at a time. Participants were told that the objects would always be located in exactly the same position so they should do their best to remember where the objects were located during the exploration phase. The last 46 participants were also told that they would take a questionnaire at the end of the exploration and navigation task.

Next, the experimenter instructed the participant on how to use the Xbox 360 gamepad to control their movement in the world. Participants controlled the yaw (i.e., panning) of their view until they thought the cross-hair pointed directly at each object (one at a time), at which point they were instructed to confirm their pointing response by pressing a button on the controller. The participants could also control the pitch, but this was not factored into the degree of error in their pointing. The experimenter monitored the participant for the first 5 min to ensure that they understood how to control their movement in the world. In pilot-testing, participants who had no experience with an Xbox controller reported getting used to it very rapidly and did not feel that it altered their performance. After participants completed the task and the questionnaire, they were asked about their video gaming experience—specifically, how frequently they play or have played first-person video games—and then debriefed about the purpose of the study.

Data Processing

We recorded the X, Y, Z positions and the direction the participant was looking (camera orientation in degrees) at 10 Hz while the participant was in the virtual environment. The X, Y, Z positions and the camera orientation data for the exploration and navigation portions of the task were then down-sampled to 1 Hz before any other analysis was performed. Next, all samples with the same X, Y, and Z values located at the starting location during the beginning and end of the trajectory were removed since these were instances in which the participant was clarifying instructions or had finished exploring and was taking a break before starting the pointing task.

Pausing Behavior The first measure we computed from the position data during the exploration phase (termed "Pausing") was calculated by dividing the total number of seconds spent paused by the total time spent exploring in the world. A pause was defined as consecutive samples with the same X, Y, and Z values, and the number of consecutive samples with the same position values was used to infer the number of seconds for a given pause. The lengths (in seconds) of the pauses were summed and divided by the total number of seconds in the exploration trajectory.

Revisiting Behavior The second measure we calculated was the extent to which the participant revisited locations (termed "Revisiting") throughout the exploration phase. First, we established a 100 m radius around each location along a participant's trajectory. The decision of 100 m was based on the maximum distance from which one could reasonably visually identify one of the objects in the virtual world. In other words, we believe that a participant could effectively search a circle with a radius of 100 m from each position in their trajectory. For each position in the participant's trajectory, the Euclidean distance between this position and all other previous positions was calculated, and all positions with a Euclidean distance equal to or less than 100 m were identified. Next, any positions that were within the 100 m radius that consecutively preceded the current position were removed since they do not indicate "revisiting" behavior per se. Therefore, revisiting positions were defined as any of the positions within the 100 m radius in which the participant left and then re-entered that area (Fig. 3). Finally, the average number of revisiting positions across all samples in the exploration trajectory was computed, indicating the overall amount of revisiting behavior.

Step Length Distribution To define a "step" in an individual's trajectory, we followed the rectangular model proposed by Rhee et al. (2011) since this model does not artificially create many small steps around curves (i.e., turns) in a trajectory. Any participant with fewer than 50 individual step lengths was excluded from any analysis involving step length distributions because it has been suggested that the estimated parameters for the fitted distribution may be untrustworthy with fewer than 50 samples (Clauset et al. 2009). Next, we used the poweRlaw package in R (Gillespie 2015) to fit a power law and a log-normal distribution to each individual's step lengths using the guidelines suggested by Clauset et al. (2009).

Spatial Memory Assessed Through Pointing and Navigation Efficiency We calculated the absolute pointing error for each of the ten pointing responses (2 pointing responses per object, once after exploring and once after navigating). Then we averaged the 10 absolute pointing error responses. Navigation efficiency was calculated by splitting the navigation trajectory into five segments. The first segment was the portion of the trajectory from the starting location to the first object. The second segment was

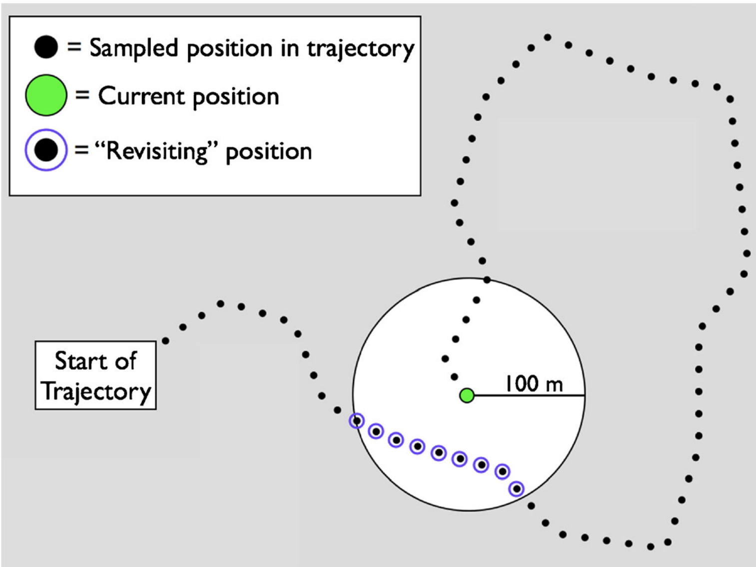

Fig. 3 Graphic representation of the revisiting measure. Points that were considered revisiting are indicated by a dot with a circle

the portion of the trajectory from the first object to the second object. The process was continued until five segments were generated, indicating the navigation path to each of the objects. Next, the discrete Fréchet distance was used to compare each navigation path to a straight line.[1] The lower the Fréchet distance, the closer the navigation path was to a straight line. Presumably, if the participant knew precisely where a given object was located, they would take the shortest (straight-line) path to that object when asked to navigate back to the object.

Results

Exploration Behavior and Navigation

We used path analysis to test our primary hypothesis that female participants will engage in more cautious exploration behavior, and our secondary hypothesis, that this will account for spatial memory as measured through navigational efficiency and/or pointing accuracy. The path model was estimated in Mplus Version 7.11 (Muthén and Muthén 1998–2102) using a maximum likelihood estimator with 1000 iterations. A bootstrapping procedure (with 500 samples) was used to provide robust estimates of standard errors. Table 1 presents the correlation matrix, means, and standard deviations for each variable in our model. All coefficients presented in the text are unstandardized values, and all of the coefficients presented in the path diagram (Fig. 4) are standardized values.

Model Results

The model we tested allowed the estimation of eight direct relationships and two unanalyzed effects (see Fig. 4). This model implies that although the participant's sex (coded as females=0, males=1) may directly predict navigation inefficiency and magnitude of pointing errors, these relationships are at least partially mediated by both revisiting and pausing behaviors. First, this model revealed that the participant's sex only predicted navigation inefficiency through the revisiting and pausing behaviors they engaged in while exploring. Specifically, males engaged in significantly less revisiting, $b_1=-8.62$, $SE=2.94$, $p=0.003$, and pausing behavior, $b_2=-0.09$, $SE=0.02$, $p<0.001$, than females. Subsequently, more revisiting behavior led to an increase in navigation inefficiency, $b_3=1.00$, $SE=0.50$, $p=0.043$. Likewise, more pausing behavior led to an increase in navigation inefficiency, $b_4=100.7$, $SE=49.4$, $p=0.041$. Both revisiting and pausing behaviors completely mediated the relationship between the participant's sex and navigation inefficiency, $b_5=-6.70$, $SE=6.85$, $p=0.328$. Next,

[1] The Fréchet distance measures the similarity between two curves by determining the minimum line length required to connect two units as they move along each curve. For example, imagine a dog owner and a dog going for a walk and taking different paths, but staying near each other to some degree. The Fréchet distance simply determines the minimum length of a leash necessary to connect the owner to the dog as they travel through their trajectory. The discrete version of the Fréchet distance is conceptually similar, but instead imagine two frogs that jump from one stone to another, creating a discrete trajectory. The discrete Fréchet distance measures the minimum line length required to connect the frogs at each stone along their trajectory.

Table 1 Correlations between participant sex, exploration behaviors, and navigation measures

Variable	1	2	3	4	5
1. Sex	–				
2. Revisiting	−0.32 **	–			
3. Pausing	−0.47 **	0.56 **	–		
4. Navigation inefficiency	−0.31 **	0.51 **	0.49 **	–	
5. Absolute pointing errors	−0.30 **	0.18	0.27 *	0.56 **	–
Mean	0.54	15.32	0.12	128.6	41.2
Standard deviation	0.52	13.5	0.09	39.32	25.1

* $p<0.05$, ** $p<0.01$

although the participant's sex was a significant predictor of pointing errors, with males demonstrating more accurate pointing than females, $b_6=-10.89$, $SE=5.30$, $p=0.040$, neither revisiting, $b_7=0.05$, $SE=0.28$, $p=0.869$, nor pausing behaviors, $b_8=39.54$, $SE=37.33$, $p=0.288$, significantly mediated this relationship (see Table 1 for standardized coefficients). Male participants ($M=2.38$, $SD=1.39$) reported significantly more video gaming experience than females ($M=1.18$, $SD=1.27$), $t_{74}=-3.89$, $p<0.001$, $d=0.903$. Importantly, after controlling for video game experience, participant sex remained a significant predictor of both revisiting and pausing behaviors, and revisiting and pausing behaviors remained significant predictors of navigation inefficiency.

Distribution of Step Lengths

First, we compared the fit of a power law distribution to that of a log-normal distribution, finding that 59 of 68 participants had a step length distribution that fit a log-normal distribution better than a power law distribution. Therefore, we further

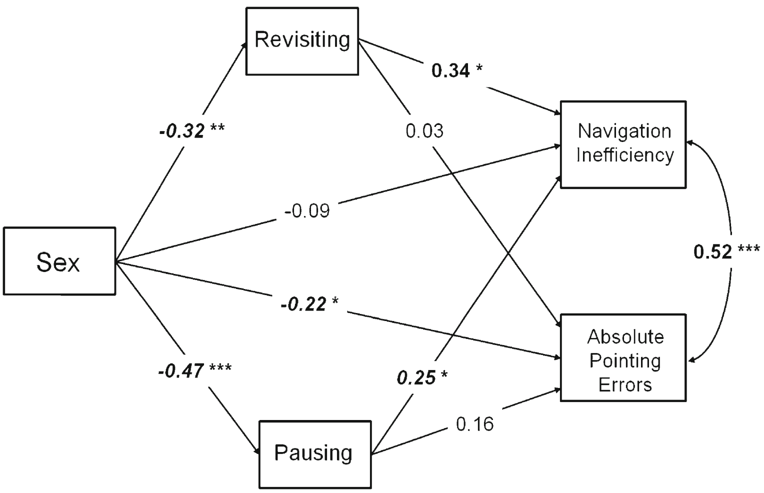

Fig. 4 Path diagram displaying how cautious exploration behaviors uniquely and completely mediated the relationship between sex and navigation performance

examined the estimates of the mean and standard deviation of the log-normal distributions. We found that male participants (M=4.57, SD=0.54) had a significantly larger log-normal mean than female participants (M=4.17, SD=0.69), t_{66}=−2.72, p<0.01, d=0.66. Female participants (M=1.06, SD=0.29) had a significantly larger log-normal standard deviation than male participants (M= 0.85, SD=0.29), t_{66}=2.98, p<0.005, d=0.72 (Fig. 5). The result of combining the log-normal mean and standard deviation for males and females was that males demonstrated a higher proportion of longer step lengths (from approximately 100 to 400 m), while females exhibited a higher proportion of short step lengths (from approximately 1 to 100 m).

Second, we expected to find that our novel measures of cautious behavior (i.e., revisiting and pausing) would be related to the distribution of step lengths, with a higher proportion of small step lengths being indicative of more revisiting and pausing. Indeed, the more revisiting and pausing one engaged in, the higher their proportion of small step lengths, revisiting with log-normal mean: r_{68}= −0.32, p=0.008 and standard deviation: r_{68}=0.47, p<0.001; pausing with log-normal mean: r_{68}=−0.57, p<0.001 and standard deviation: r_{68}=0.55, p<0.001.

Finally, participants who explored with a higher proportion of long step lengths demonstrated less navigation inefficiency, log-normal mean with navigation inefficiency: r_{68}=−0.32, p=0.008, and log-normal standard deviation with navigation inefficiency: r_{68}=0.37, p=0.002. Overall, the proportion of long step lengths (i.e., heavier distribution tail) appears to be more indicative of male participants, who seem to be less cautious explorers and overall more efficient navigators.

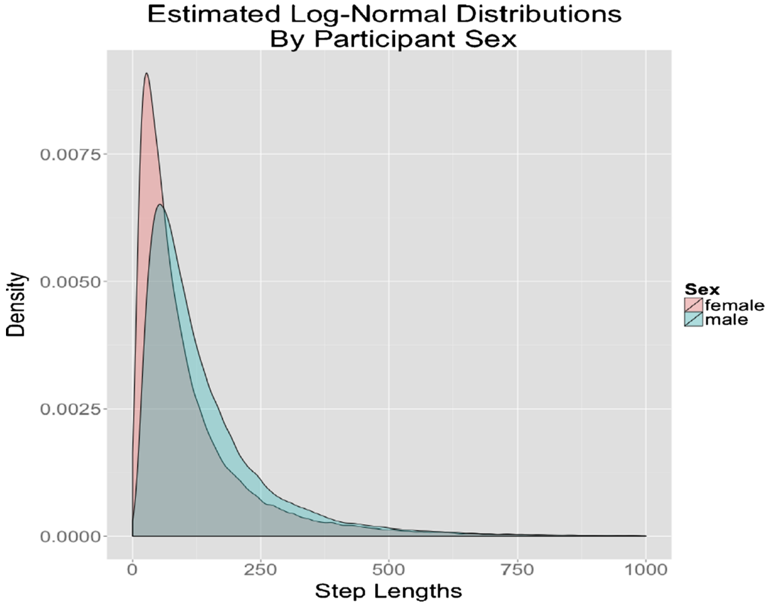

Fig. 5 Estimated probability density functions for male and female step length distributions. Males demonstrated a higher proportion of longer step lengths

Harm Avoidance and Exploration Behavior

Our main hypothesis that females would explore a novel environment more cautiously than males (subsequently accounting for navigation performance) was supported by the path model and the correlations observed with step length distributions. The underlying reason for the expected sex difference in cautious exploration is the increased cost associated with traveling long distances, especially in unknown environments. Of the 78 participants who completed the exploration task, 46 (20 females, 26 males) also completed the 26-item harm avoidance questionnaire. If the behavioral measures of revisiting and pausing reflected overall caution while exploring a novel environment, then we would expect these behaviors to correlate with the participant's level of harm avoidance. Indeed, increased levels of harm avoidance related to increased amounts of revisiting behavior while exploring in the virtual environment, $r_{45}=0.391$, $p=0.007$ (Fig. 6), and approached a significant relationship with the amount of pausing behavior in the virtual environment, $r_{45}=0.280$, $p=0.056$.

Discussion

Much of the evolutionary literature has focused on the benefits conferred upon males for exploring new locations or traveling long distances; however, there is simultaneously an increased cost for females to do the same. First, we hypothesized that the increased costs associated with exploring new locations for females would be reflected in differences in exploratory behavior in a novel environment. As such, we operationalized cautious exploration by measuring the amount of pausing behavior and the extent to which a person revisited previous locations while exploring a novel environment. In support of our hypothesis, female participants spent a higher proportion of time paused and exhibited more revisiting behavior than male participants, suggesting that female participants were more cautious when exploring a novel environment. Previous research frequently reports that males outperform females in a variety of navigation tasks. How an individual explores a novel environment will likely have an impact on the quality of spatial information to which they were exposed, possibly influencing their ability to navigate in that environment at a later point in time. Our second hypothesis was that the sex differences in exploratory behavior may account for the sex differences in navigation performance. In support of this hypothesis, we found that more cautious exploration led to worse navigation performance when attempting to return to previously visited locations. We think it likely that the well-documented sex difference in harm avoidance underlies this effect because harm avoidance was associated with revisiting, and the path analysis showed full mediation of revisiting on navigation performance. This does not mean that sex differences in spatial ability may not also be directly associated with differences in how women and men explore novel spaces and their success in navigating through them, but it does indicate that a cautious style of exploration is an important route by which that happens. To our knowledge, this is the first experiment to quantify cautious behaviors while exploring a novel environment, relate these data to subsequent spatial memory through navigation, and relate harm avoidance tendencies to exploration behaviors.

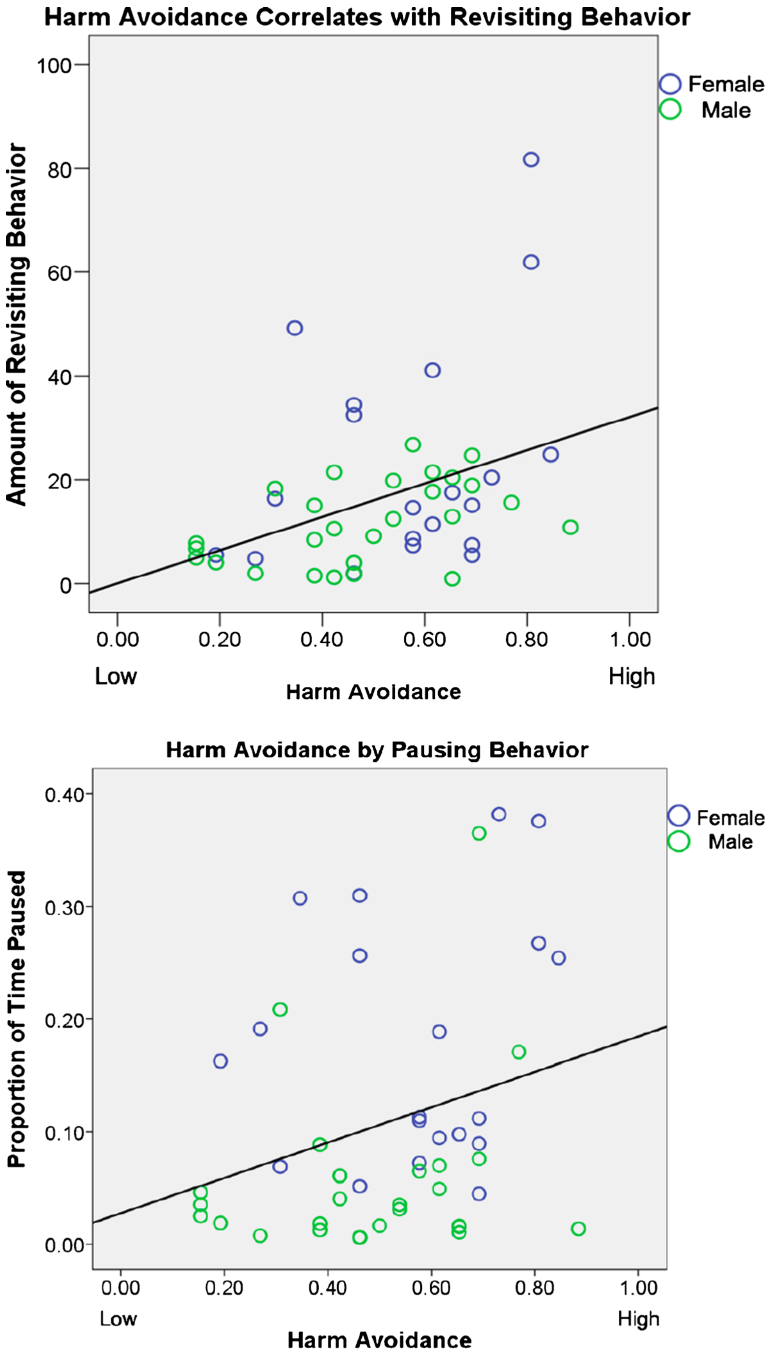

Fig. 6 Scatterplot with best-fit lines displaying the relationship between harm avoidance and revisiting and pausing behaviors during exploration

We also found that both males and females explored in patterns consistent with a truncated Lévy walk. A Lévy walk is a spatial pattern typically applied to animal movements because it tends to describe their movement very well. Recently, some work has demonstrated that humans exhibit movement patterns similar to a Lévy walk (Raichlen et al. 2014). In particular, movement patterns with a power-law distribution of step lengths are consistent with a Lévy walk pattern. Step lengths are typically defined as the distance one travels between pauses or significant changes in heading direction. In the current experiment, males tended to travel longer distances before turning or pausing than females. Conceptually, this is the inverse of revisiting and pausing behavior, adding support for our main hypothesis. Previous research in real-world mobility has demonstrated human movements to be consistent with a Lévy walk (Raichlen et al. 2014), and in some cases a truncated Lévy walk (Rhee et al. 2011). We believe the reason we observed a truncated Lévy walk was due to a boundary encompassing the virtual world that likely constrained the movement of the participants. Likewise, a number of participants reported a strategy in which they walked to the edge of the virtual world and circled the perimeter in search of the objects. In the real world, or perhaps a larger virtual world, this strategy might not be an option if the boundary encompassing the searchable terrain is much larger. Therefore, the medium and long step lengths observed in our study would likely become even longer if no artificial boundary of the environment existed, ultimately producing a pattern more consistent with a standard Lévy walk. Thus, our work shows that males and females explore differently and that this exploration may lead to more efficient navigation strategies for males when they are asked to navigate a previously explored environment.

Many studies assess navigation ability through one's ability to point accurately to unseen, but known, locations. We asked participants to return as quickly as possible to each object and to point in the direction of each target from the starting location. Our navigation efficiency metric (Fréchet distance) measured the similarity between one's navigation path and a straight line to each object, ultimately serving as a direct measure of navigation ability. Although our measures of navigation efficiency and traditional pointing both require memory of target locations, surprisingly we found that exploration differences only predicted the navigation efficiency measure and not pointing accuracy. This could be because participants had to point to each object from the starting location, but they originally found each object from the location of a previously discovered object, with the exception of the first object they found. Thus, most of their experience with the location of the objects was relative to the location of the other objects, not the starting location. Prior work has sometimes asked participants to point to objects from each other (i.e., "you are standing at the hut; point to the well"; see Shelton and McNamara 2001), so this measure could be used in future work to investigate relationships between exploration behaviors and spatial memory. Using two different measures of spatial memory as we did in the current study provides the additional contribution of evaluating measures of spatial memory. Quantifying the actual navigation performance (deviation from a straight-line path to object) is a better measure of spatial memory because it frames the memory task in the context of goal-directed navigation. Furthermore, the more efficient navigators did have significantly smaller pointing errors (i.e., there was a correlation in the path model between these two DVs). Although virtual-world rather than real-world exploration has drawbacks in ecological validity, there are some compensating advantages. Virtual exploration allowed us to ensure that the space would be equally novel to all participants, and it avoided distractions from other individuals and weather changes that could affect cue visibility. In addition, using a real-world space requires physical exertion for participants, which is especially problematic for an exploration task because of its open-ended nature. We did not want some participants to explore less because they were simply tired of walking. We tried to address some of the concerns by making our virtual environment large, realistic, and varied. Furthermore, a body of literature suggests that similar spatial processing mechanisms support navigation in real and virtual environments (e.g., Richardson et al. 1999).

In addition to the constraints of the virtual world in terms of possible exploration, there were some other limitations in the current work. Although we believe that the increased costs to females while exploring new locations is reflected in their cautious exploration behaviors exhibited in this experiment, the virtual world itself did not impose any real fitness costs (e.g., getting lost, encountering predators). Anecdotally, a number of individuals expressed concern and frustration with getting lost, but this may or may not be similar to what they would experience when exploring a real environment. Future research might consider imposing costs for traversing a virtual environment (e.g., requiring real energy to locomote, being rewarded for avoiding predators). Second, our virtual world was somewhat sparse in terms of vegetation, and this may have served as a further source of frustration while navigating. For example, the area around the starting point had very few proximal cues to indicate the direction of travel or the location of the target objects. In future work, we will consider providing more vegetation to increase the number of navigational cues. Finally, the exploration of the environment was completely visually driven. Participants controlled their movement through the environment with a game controller, not with their own motion. It is possible that females rely on proprioceptive and vestibular cues that are produced in self-motion to have a better understanding of their navigation patterns and the layout of the environment. If that is the case, then some of the apparent differences could have been a result of the lack of body-based cues. While this work serves as an important starting point for examining exploration behavior, we acknowledge that it will be beneficial to examine the contribution of vestibular and proprioceptive information to paradigms such as ours in the future.

Conclusions

Despite some limitations, the findings presented here are the first to show differences in exploration of a novel environment between males and females. Importantly, the pattern of exploration in females supports the hypothesis that they may be more cautious and risk averse. Moreover, this cautious behavior may be related to individual differences in the desire to avoid harm. Finally, cautious exploration leads to a decrease in the ability to navigate back to previously visited locations in the environment. However, it does not appear to influence one's ability to point accurately to the previously visited locations. Overall, this work supports the hypothesis that females may explore environments differently than males in order to reduce the likely costs and consequences associated with navigating new environments.

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