Cognition 180 (2018) 108–117

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/cognit

Original Articles

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

Kyle T. Gagnon[a], Brandon J. Thomas[a], Ascher Munion[a], Sarah H. Creem-Regehr[a], Elizabeth A. Cashdan[b], Jeanine K. Stefanucci[a,*]

[a] Department of Psychology, University of Utah, United States
[b] Department of Anthropology, University of Utah, United States

ARTICLE INFO

Keywords:
Navigation
Spatial memory
Gender differences
Exploration

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

* Corresponding author at: University of Utah, Department of Psychology, 380 S 1530 E, Room 502, Salt Lake City, UT 84112, United States.
E-mail address: jeanine.stefanucci@psych.utah.edu (J.K. Stefanucci).

https://doi.org/10.1016/j.cognition.2018.06.020
Received 30 August 2017; Received in revised form 24 June 2018; Accepted 26 June 2018

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