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The Development of Spatial Navigation Ability from Childhood to Adulthood

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Abstract

Spatial navigation is critical for organisms to navigate their way around an environment. Prior evidence shows age and sex differences in spatial navigation ability, with older participants requiring longer time, longer distance, and more complex paths to reach their target. However, the developmental trajectories of spatial navigation from childhood through young adulthood have not been previously studied. Spatial navigation performance was tested using a virtual Morris Water Maze task in 71 participants aged 5-21 years (M= 10.41, SD= 4.62). Each participant completed 15 navigation trials, during which they used a joystick to reach a platform hidden under the water in the virtual swimming pool. To measure the spatial navigation ability, time, distance, and complexity or fractal dimensionality (FD) of the paths that participants traveled to reach the target were calculated. Additionally, age and sex effects on navigation performance were tested. Adult and adolescent participants and males performed better, such that older participants traveled shorter distances and males traveled less complex paths than females.

Keywords: Spatial Navigation, Fractal Dimensionality, Morris Water Maze

1. Introduction

Individuals live in spatially complex environments and rely on complex processes to represent their environment and effectively navigate in it. Spatial navigation is the ability that allows individuals to effectively find their way in an environment and reach specific target locations. Successful spatial navigation is thought to be possible due to the formation of a complex cognitive map. A cognitive map is an internal representation of an environment formed by using surrounding cues.[1] Cognitive maps are formed while individuals navigate through the environment, and effective learning of a cognitive map is crucial for children and adults.[1] Successful formation of cognitive maps leads to progressive increase in spatial navigation ability across numerous trips through a certain environment.

Age-related differences in spatial navigation ability have been identified in previous research.[1,2,3] Progressive decrease in spatial navigation ability has been demonstrated in studies with older adults, but little is known about how spatial navigation ability changes during child development.[2] That is, it is not clear how navigation ability is related to an individual's age specifically in the age range between early childhood to young adulthood. Some evidence suggests maturation of an ability to process spatial information in large contexts occurs around the age of 8 years and similar age-related improvement was documented using computerized navigation tasks around the age of 9 years.[3,4,5] This project aims to characterize developmental trajectories in spatial navigation ability in children and adolescents.

Sex differences in navigation ability have also been identified in previous research and a male advantage in spatial navigation ability is well documented in adults.[2] It remains unclear, however, whether a sex effect interacts with age from childhood to adulthood. Specifically, in an adolescent and adult sample it was shown that age-related improvements in spatial navigation ability are larger in males compared to in females. However, similar differences between the sexes have not been documented in children. Thus, an additional aim of this project is to characterize the developmental trajectories in spatial navigation in children and adolescents, while exploring how potential age effect may interact with sex in affecting individual's navigation ability.

A commonly used task to assess spatial navigation in rats is the Morris Water Maze (MWM) task. In the MWM, a rat is placed into a large circular pool of water in search of a platform to rise above the water and escape from the pool, with the guidance from distal visual cues surrounding the pool.[6,7] The adapted virtual MWM (vMWM) task mimics the search for the submerged platform with a computer game for human participants, who used a joystick to navigate through a virtual pool presented on a computer screen. Two measures were used to quantify spatial navigation performance. First, the time and distance traveled to reach the platform were measured. A third measure, fractal dimensionality (FD) of the travelled path was also calculated and used as an index of path complexity.[2] These three behavioral indices provide complementary information about an individual's navigation ability.

In sum, this study is aimed to fill a gap in the understanding of the development of spatial navigation ability across children, adolescents and young adults and assessing differential outcomes across males and females.

The development of spatial navigation was investigated using vMWM task and age differences in time, distance, and FD of travelled paths were assessed. Finally, to uncover developmental differences that may relate to sex age differences were assessed separately for male and female participants.

2. Materials and Methods

2.1 Participants

A total of 71 healthy participants aged 5-21 years (M=10.21, SD=4.62) were tested over the course of this study. Participants took part in additional assessments that are beyond the scope of the current report. Thirty-five participants were between ages 5-7 (M=6.11, SD=0.62, 19 females/16 males), 14 were between 8-12 (M=1.15, SD=1.10, 6 females/8 males), 17 were between 13-17 (M=15.12, SD=1.71, 7 females/10 males) and five were 18 and older (M=19.31, SD=0.95, 2 females/3 males). Participants were recruited from Wayne State University's student body and from the metro Detroit communities through educational outreach events as per an IRB approved protocol, through Fall of 2014 to Winter of 2017. Participants had no reported developmental or neurological disorders, and no history of head trauma. Participants were compensated for their time and reimbursed for parking. Parents of all participants provided informed consent and child participants were asked to assent to participation in the study either verbally or in writing. Participants were told they could withdraw from the study at any time and for any reason.

2.2 Testing Procedures

All participants completed the virtual Morris Water Maze (vMWM). Twenty-five trials of vMWM were administered to the participants ages 7 years and older, participants ages 5-6 years were only given 15 trials given the expected difficulty to remain engaged in multiple iterations of the same task in this age range. To allow for combining measures from all participants, across all ages, only the first 15 trials were included in all data analyses.

2.2.1 *practice*

Prior to the start of testing trials, participants were introduced to the virtual environment by being placed inside a 'practice pool'. They were trained to manipulate the joystick and were asked to practice steering forward, to the right and to the left. After practicing manipulating the joystick, participants were asked to navigate to five different visible platforms located throughout the 'practice pool'. The room around the practice pool did not contain any visual cues. Once the participant felt comfortable navigating around the pool, they were administered the test trials.

Figure 1. View of participant engaged in spatial navigation test trial.

2.2.2 *virtual Morris Water Maze*

After completion of the practice trials, participants were given a series of five trials in a pool that was similar to the 'practice pool', except that there was only one platform that was hidden in the water (see Figure 1). The participants were asked to use the joystick to navigate in the pool until they successfully arrived at the platform location, which resulted in the platform rising above the water and becoming visible. The room around the test pool contained two distal cues and five proximal cues to assist in the navigation process. The participants were given up to two minutes during each trial to locate the platform, after which the system would time out. The cues in the room and the location of the platform remained constant across all trials but there were five different starting locations that were used consecutively. The order of the starting locations was counterbalanced by age and sex. At the end of the trials, distance and time traveled to reach the platform and path FD measures were collected.

Since age related individual differences in fine motor skills can influence joystick control, participants were asked to complete a final swim trial. In the final swim task, participants were instructed to swim as fast as they could to the center of four red flags, which corresponded to the location of the platform. The distance and FD of the path traveled in this swim trial were treated as the baseline measure for individual differences in joystick control. Secondly, participants or their parents completed a three-item Computer Experience Questionnaire with the third item specifically asking how often the participants play 3D environment simulated computer games. This questionnaire served to control for familiarity with video games and 3D environments.

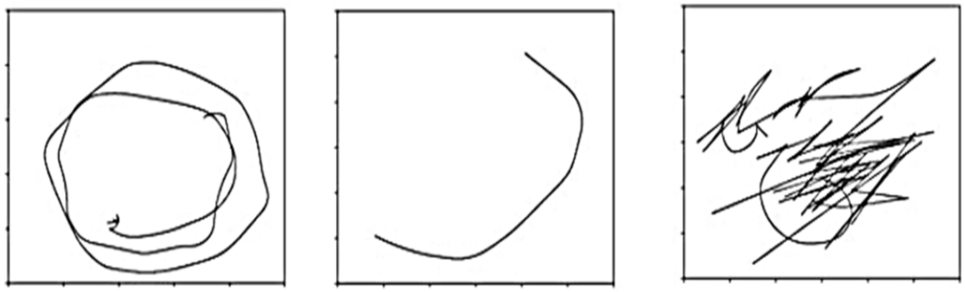
2.3 Measures

2.3.1 *distance and time traveled*

Distance and time traveled to locate the hidden platform and path FD measures were collected across the trials for each participant. FD is thought to reflect aspects of the cognitive map one possesses and can be differentiated from measures of distance during navigation.[1] The complexity of a path as measured by FD indicates the cognitive mapping processes utilized when navigating an environment.[1] Average time was measured in log seconds with average distance measured in log virtual units as generated from the Fractal program created at Dalhousie University.[8]

2.3.2 *fractal dimensionality*

Fractal Dimensionality (FD) is a continuous measure of geometric properties of an object confined to a plane.[2] FD is also measured in log virtual units using the aforementioned Fractal program.[9] Higher FD suggests increasing randomness and uncertainty in the search pattern. FD of the search paths were calculated with the x, y coordinate output using the Fractal Software.[8] Fractal was previously used to study path complexity and volumetric measurements for participants aged 18-77.[2] See Figure 2 for an example of fractal dimension values calculated for several example paths.



FD=1.03 FD=1.03 FD=1.09

Figure 2. Examples of FD graphs and corresponding scores. The first two graphs have the same FD values although the distance travelled is different. The participants with FD = 1.03 showed less complex paths. However, the participant with an FD = 1.09 had a more complex path showing they had a poor cognitive map and sense of where the platform was located. Participants with higher FD values used a more complex path to reach the platform, indicative of poor spatial navigation ability.

2.4. Statistical Analysis

To examine age and sex effects in spatial navigation performance, three General Linear Models (GLMs) were conducted with average time, average distance and FD as the dependent variables, age and sex as the independent variables. All analyses were controlled for individual differences in handling the joystick as measured by swim trial distance and FD. In addition, all analyses were controlled for individual differences in experience in 3D computer environments measured with a parent's reported questionnaire containing information about how often each week, on a scale of 1 to 7, their child used computers and how often a child was exposed to computerized 3D environments. Analyses were controlled by adding measures as covariates to the GLM.

3. Results

In this study, three indices of spatial navigation—average time, average distance and average path complexity (FD) were used to assess the link between spatial navigation and participant's age and sex.

Overall improvement in performing the spatial navigation task was assessed by testing the three indices of spatial navigation in Trial 15 compared to Trial 1. Performance on trial 15 was better compared to Trial 1 as evidenced in shorter time to reach the platform ($t(61)=5.51$, $p<0.001$), shorter distance traveled ($t(61)=4.90$, $p<0.001$), and lower FD scores ($t(61)=2.16$, $p=0.04$) (Figure 3).

Next, the average of all 15 trials was used in assessing whether average scores in the three indices of spatial navigation differed by participant's age, sex or the interaction of age and sex.

Time to reach the platform. Age and average time to reach the platform were negatively correlated ($r=-.47$) across participants ($F(1,64)=12.92$, $p<0.01$). Older, compared to younger, participants required less time to reach the platform, indicating better spatial navigation ability. There was no significant age by sex effect on time in the current sample, such that the relation between age and time did not differ between sex.

Distance traveled. Age and average distance to the platform were negatively correlated ($F(1,64)=31.41$, $p<0.001$), with older participants travelling shorter distances to reach the platform. Older, compared to younger, participants required less distance to reach the platform, indicating better spatial navigation ability for the index of distance. There was no significant age by sex effect on distance in the current sample, such that the relation between age and distance did not differ between sex. Overall, when considering time to reach the platform and the distance traveled the findings suggest that older, compared to their younger participants, demonstrate better spatial navigation ability (Figure 5).

FD, an index to reflects the complexity of a cognitive map of the environment. Across age, there was a main effect of sex on FD ($t(69)=-3.63$, $p=0.001$). As shown in Figure 4, males had significantly lower FD scores than females, suggesting that they required less complex paths on average across the 15 trials to reach the platform. In contrast to findings based on time and distance, when considering FD there was a significant difference in age patterns between males and females as shown in Figure 5, such that the relation between age and FD differed significantly between males and females (*F*(1,62)=4.52, *p*=0.04). This interaction suggests a potential differential development of spatial navigation ability between males and females. Follow-up analyses showed that age and FD were not significantly related in either males (*F*(1,32)=2.22, *p*=0.15) or females (*F*(1,27)=1.98, *p*=0.17), though the relation pattern between age and FD differed significantly between males and females. These findings suggest that some aspects of spatial navigation ability may show sex differential age differences. In males compared to females, there was an age-related decrease of fractal dimensionality suggesting in males more so than in females, an age-related improvement in formation of cognitive maps for navigation.

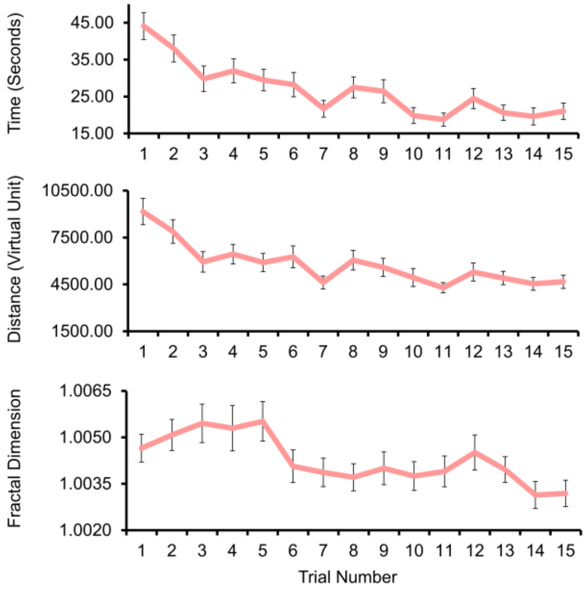


Figure 3. Average, across participants of three measures of spatial navigation used in this study plotted per each of the 15 trials tested. Performance on Trial 15, compared to Trial 1 was significant better in all three measures. *Top*, Time to reach the platform (sec: *t*(61)=5.51, *p*<0.001); *Middle*, Distance travelled (arbitrary units: *t*(61)=4.90, *p*<0.001); *Bottom*, Fractal dimensionality, indicating path complexity (FD: *t*(61)=2.16, *p*=0.04).

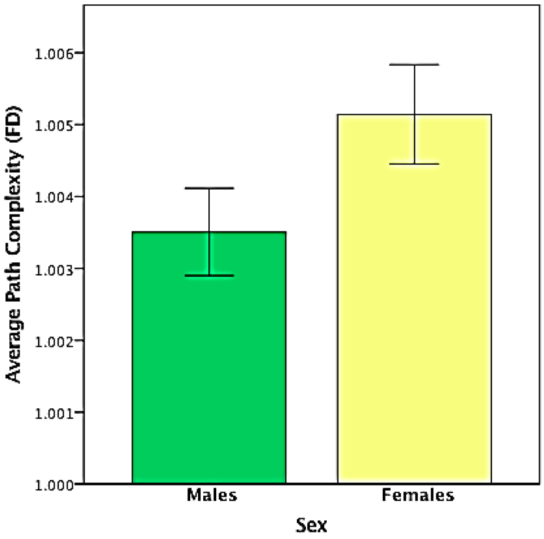


Figure 4. Path complexity, as assessed with a measure of fractal dimensionality in the observed path, differed by sex. Males used less complex paths (*t*(69)=3.63, *p*=0.001), indicating better cognitive maps. The error bars represent standard error.

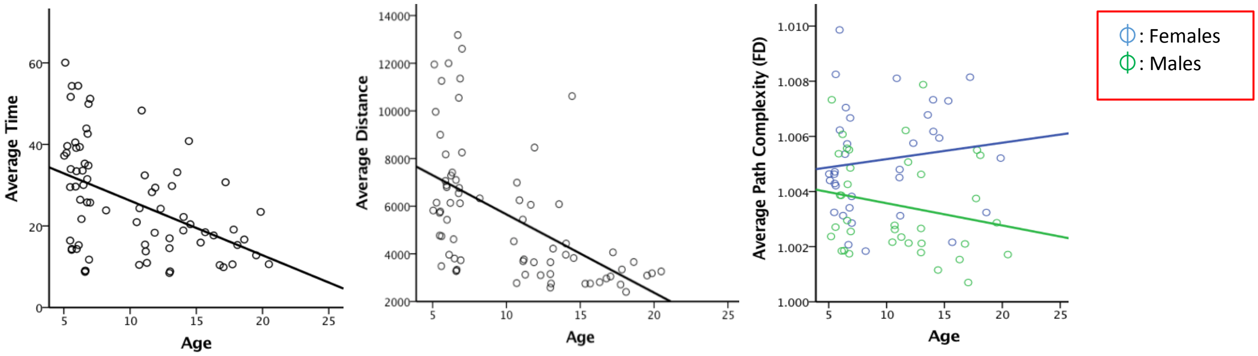


Figure 5. Average time to reach the platform, distance travelled, and path complexity as a function of age (years) and sex. Average time to reach the platform (sec), distance travelled (arbitrary unites), and path complexity (fractal dimensionality, FD) were measured across 15 trials and plotted per participant. Negative correlations with age, regardless of participant's sex, were found for the measures of time ($F(1,64)=12.92$, $p=0.001$) and distance ($F(1,64)=31.41$, $p<0.001$). The pattern of age correlations with path complexity (FD) differed between males and females ($F(1,62)=4.52$, $p=0.04$).

4. Discussion

The development of spatial navigation ability from childhood to adulthood was tested in this study. Spatial navigation ability was examined in participants ages 5-21 years who completed 15 trials of navigating to a hidden target within a virtual Morris Water Maze. Effects of both age and sex on spatial navigation ability were tested.

The within session improvement in spatial navigation was tested by comparing scores in navigation indices on trial 15 to those in trial 1. Overall, the improvement between trial 1 and trial 15 on all indices indicated that participants located the platform faster, traveled shorter distances, and established better cognitive maps. These findings suggest that participants learn to efficiently navigate in an environment across the trials. Previous studies using a similar task identified within session improvement in spatial navigation of the learned environment. For example, when participants ages 19-75 were tested in the virtual Morris Water Maze using 25 trials, both the average distance traveled to reach the platform and the complexity of the path (indicated by FD) decreased across trials.[1] The findings provided in the present study are consistent with prior reports and show that over 15 trials participants become faster, travel shorter distances, and use less complex paths in reaching a hidden platform.

A main goal in this investigation was to assess age difference in navigation ability. Indeed, older participants were faster and traveled shorter distances to reach the platform indicating age-related improvement in spatial navigation ability as compared to their younger still developing counterparts. Previous studies have looked at this relationship in healthy aging populations and have found that spatial navigation ability decreases across the indices of time, distance and fractal dimensionality with advanced age.[1,2] It has been shown that in an aging population, advanced age is associated with longer search time, longer traveled distance, and larger FD.[2] In our population of 5-21 year olds, there was a negative association between increased age and both time and distance to reach the platform, indicating age related improvement in spatial navigation ability. Future studies can assess the relation of age to spatial navigation ability across the lifespan.

Age differences in path complexity differed between males and females, with an age-related decrease in path complexity (FD) in males, but not in females. These findings are consistent with previous findings showing that spatial ability increases to a larger extent in males compared to females.[3] On average, across the 15 trials, males had significantly lower FD scores than females, suggesting males used more efficient paths reflecting the use of better cognitive maps during navigation. Independent of age, however, female traveled paths that cover longer average distances and higher a FD of path when compared to men. Nonetheless, there was no sex difference in travel times suggesting that different indices of spatial navigation may capture different aspects that differ in their association with sex.[2]

Prior studies have estimated sex differences in a similar task. For example, in one study investigators did not find main effect of sex for average travel distance (path length, as a ratio of the pool diameter) or latency (time to reach a target) assessed over 16.[3] In contrast, sex differences were identified when immediately after training the investigators assessed participants' navigation in the environment with a 'probe trial' in which the target was not present. Males, compared to females, were faster in reaching the quadrant where the target was originally in and they took a shorter path to entering that relevant quadrant. Males also showed smaller heading error, or the angular deviation from the path from the release point to the platform. These findings suggest sex differences in navigation and that males may be utilizing better cognitive maps. Participants' path length to first enter this circular region as well as the total percentage of overall path length within this region were calculated. There was no significant age by sex interaction observed for any measure in this study. The findings from our study help build on these observed sex differences in path length or distance by providing information on the difference in path complexity (FD) between the sexes, specifically in a developing population.

One possibility that we can partially rule out as contributing to sex differences is prior experience with computers and exposure to computer games in which the player navigates in a 3D computerized environment. We can rule this out because prior experience was controlled for in all models. However, although computer experience was controlled for in the GLMs, increased male exposure to video games and 3D environments could still play a role in this age-related decrease of FD in males. Indeed, research with adults showed that women had less 3D gaming experience than males and performed worse on the final swim trial measuring joystick control.[1] Future research could address these sex differences in FD scores.

Overall, we identified age-related improvement of spatial navigation ability and age dependent differential development between males and females.

5. Future Directions

The hippocampus plays a critical role in forming a cognitive map and in encoding object information in the environment.[9,10,11] Future investigation will focus on the relationship between the indices of spatial navigation ability (time, distance, FD) and hippocampal total volume and hippocampal regional volumes including hippocampal subfield volumes. Indeed, across the adult lifespan, smaller hippocampal volume is associated with a decreased ability to navigate effectively, as evidenced in a more complex path when navigating to a target.[2] Previous results show that total hippocampal volume is associated with change in FD across trials in a sample of 139 adult participants aged 18-77.[2] These findings may relate to findings of hippocampal atrophy with advanced age and in people with neurodegenerative disorders such as Alzheimer's.[12] Little is known about the relationship between hippocampal volume and navigation ability in child development. However, there is growing interest in identifying the neural substrates that support the development of spatial navigation, as recent evidence suggests that the hippocampus may undergo protracted development.[1,13] Analyses of the link between behavioral indices of spatial navigation and hippocampal volumes will allow to better identify the relation between hippocampal structure and spatial navigation ability.

Of specific interest will be examining the association between volume of hippocampal subfields and participants' age. Individual subfield volumes were correlated with reduction in path complexity in a previous study of 65 participants aged 19-75 and larger subiculum and entorhinal cortex volumes were associated with faster decrease in path complexity.[1] Association between indices of spatial navigation and hippocampal subfield volumes, however, were found independent of age, suggesting that individual differences in subfield volumes amongst children, adolescent and adult participants may also relate to individual differences in spatial navigation performance. For the majority of participants included in this report information exists regarding hippocampal volume, obtained based on manual tracing of the hippocampus on high resolution MR image from each participant.

Another topic for future investigation is determining additional aspects of learning to navigate in the virtual pool. Specifically, one may calculate the slope of the learning and the level at which learning gains no longer exhibited within a session (i.e., the asymptote). These additional measures can provide information about individual differences in the rate of acquiring information crucial for effective spatial navigation. Of interest in estimating the relation between hippocampal regional volumes and avigation, consistent with prior report[1] we predict that smaller volumes of the entorhinal cortex may be associated with slower acquisition, but unrelated to differences in asymptotic performance.

Finally, spatial navigation is facilitated by the inclusion of specific cues in the environment. Previous research has shown that advanced age-related deficits in spatial navigation ability are due to impairment in landmark cue recognition and subsequent formation of cognitive maps.[1] Additionally, previous work with rats has shown that aged, compared to younger, rats require more trials to reach asymptote in performance. These age-related deficits have been related to poor integration of landmark cues and declines in spatial working memory.[2] In the virtual Morris Water Maze use here, location of proximal and distal cues aided in the formation of a cognitive map, making it easier to find the platform across trials.[1] We used 5 proximal cues surrounding the perimeter of the pool (fountain, tires, trees, columns and a lamp) and 2 distal cues (distinct notches in the outer wall). The cues remain in the same location of the pool and relative to each other, therefore providing consistency in extracting information about the environment in which participants navigated. Future directions will include testing the degree to which the cues were incorporated into the participants' cognitive maps contributing to the improvement in time, distance and FD across trials. These additional directions will provide information important for our understanding of the development of spatial navigation and its reliance on hippocampal function.

6. Conclusion

In this study age differences in spatial navigation ability were examined in participants ages 5-21 years who were given 15 consecutive trials in a virtual navigation environment. Using the indices of time, distance and path complexity measured by FD, it was found that on average over repeated trials, participants improve as indicated by significantly shorter time and distance traveled and less complex paths to reach the platform. Age differences emerged in the data such that older participants showed better spatial navigation performance—travelling shorter distances and requiring less time to reach the platform. A trend of age-related decrease in path complexity (FD) was observed in male, but not in female participants. The findings of this study add to the growing body of research on spatial navigation ability and strengthen the previous findings that the development of a cognitive map improves navigation ability.

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9. References

1. Daugherty, A. M., Bender, A. R., Yuan, P., & Raz, N. (2015). Changes in search path complexity and length during learning of a virtual water maze: age differences and differential associations with hippocampal subfield volumes. *Cerebral Cortex 26*, 2391-2401.
2. Daugherty, A. M., Yuan, P., Dahle, C. L., Bender, A. R., Yang, Y., & Raz, N. (2015). Path complexity in virtual water maze navigation: differential associations with age, sex, and regional brain volume. *Cerebral Cortex 25*, 3122-3131.
3. Sneider, J. T., Hamilton, D. A., Cohen-Gilbert, J. E., Crowley, D. J., Rosso, I. M., & Silveri, M. M. (2015). Sex differences in spatial navigation and perception in human adolescents and emerging adults. *Behavioural Processes 111*, 42–50.
4. Laurance H. E., Learmonth A. E., Nadel L., Jacobs W. J. (2003). Maturation of spatial navigation strategies: Convergent findings from computerized spatial environments and self-report. *Journal of Cognition and Development 4*, 211–238.
5. Overman W. H., Pate B. J., Moore K., Peuster A. (1996). Ontogeny of place learning in children as measured in the radial arm maze, Morris search task, and open field task. *Behavioral Neuroscience 110*, 1205-28.
6. Jacobs, W. J., Laurance, H. E., Thomas, K. G. F. (1997). Place learning in virtual space I: Acquisition,

overshadowing, and transfer. *Learning Motivation 28*, 521-541.

. Morris, R. G. M. (1981). Spatial localization does not require the presence of local cues. *Learning Motivation 12*, 239-260.

8. Nams, V. O. (2006). Improving accuracy and precision in estimating fractal dimension of animal movement paths. *Acta Biotheoretica 54*, 1–11.

9. O'Keefe, J. (1991). An allocentric spatial model for the hippocampal cognitive map. *Hippocampus 1*, 230-235.

10. Moffat, S. D., Zonderman, A. B., Resnick, S. M. (2001). Age differences in spatial memory in a virtual environment navigation task. *Neurobiology Aging 22*, 787–796.

11. O'Keefe, J., & Nadel, L. (1978). The hippocampus as a cognitive map. *Oxford: Clarendon Press*, 2-3.

12. Apostolova, L. G., Green, A. E., Babakchanian, S., Hwang, K. S., Chou, Y.-Y., Toga, A. W., & Thompson, P. M. (2012). Hippocampal atrophy and ventricular enlargement in normal aging, mild cognitive impairment and Alzheimer's disease. *Alzheimer Disease and Associated Disorders 26*, 17–27.

13. Daugherty, A. M., & Raz, N. (2017). A virtual water maze revisited: Two-year changes in navigation performance and their neural correlates in healthy adults. *NeuroImage 146*, 492-506.