Evaluating Age-Related Cognitive Map Decay Using a Novel Time-Delayed Testing Paradigm

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Abstract. A critical component of effective navigation is the ability to form and maintain accurate cognitive maps. Proper cognitive map maintenance can become difficult for older adults as many of the constituent memory structures exhibit degradation with age. The present study employed a novel testing paradigm where younger adult participants (20 to 40 years) and older adult participants (60 to 80 years) learned a virtual environment through free exploration using an immersive driving simulator. After the learning phase, participants immediately sketched a map of the course. As forming an accurate baseline cognitive map was critical to this methodological procedure, they were provided additional learning time if placement of landmarks and roads were not within a given accuracy tolerance. Upon meeting criterion, participants completed egocentric and allocentric pointing tasks. Following this lab-based testing, participants were given 2 packets containing the exact same map sketching and pointing tasks to complete one-day and one-week after the study. Results showed clear age group differences, with older adult map sketching and pointing performance being significantly worse than their younger counterparts. There was also a clear numeric trend showing declines in performance for the older adults at the delayed-testing time intervals as compared to the in-lab testing. These findings suggest that the stored cognitive maps of older adults may exhibit greater decay over time as compared to younger adults. Future studies using this new methodological paradigm will be helpful in further elucidating the processes underlying spatial knowledge decay in older adults.

Keywords: Spatial cognition · Driving · Aging · Virtual reality · Navigation

1 Introduction

As humans move through and learn about the environment, we develop mental representations of surrounding space that may aid subsequent navigation. These long-term memory structures are known as cognitive maps, which are spatial representations formed in the hippocampus that contain information such as routes, landmarks, and the

allocentric relations between them [1–3]. Development and maintenance of accurate cognitive maps is critical to everyday navigation. Previous research has found that while older adults frequently show preservation of certain spatial abilities, e.g. egocentric tasks, they also often exhibit decline in others, including cognitive map formation and access (for review, see [4, 5]). In addition, little is known about changes (or decay) in spatial knowledge representations over time once the information is no longer being reinforced through explicit learning or direct perception, especially for older adult populations.

The goal of this work was to investigate the decay function of the cognitive map and characterize how the aging process influences this decay. The present study focuses on normal transformations of spatial processes rather than more extreme fluctuations experienced as a result of disease or impairment; thus highlighting a healthy and natural aging process. The current work also defines and evaluates a new methodological paradigm, which was designed to provide a rigorous experimental approach for characterizing changes in spatial memory at key times over the most susceptible interval of temporal decay. The knowledge gained from the current work is important for (1) improving our understanding of changes in spatial abilities that occur across the life span, (2) guiding innovative research aimed at further characterization of the decay of spatial knowledge for older adults, and (3) Providing guidelines for the development of assistive technologies aimed at supporting the maintenance of spatial knowledge found to be most susceptible to age-related decay.

After a cognitive map is formed, the navigator must maintain the integrity of this mental representation in order to perform subsequent spatial operations during navigation. The present work investigated whether learned environmental information decays more over time for older adults than younger adults, even when both groups have formed equivalent baseline cognitive maps, as assessed by meeting criterion on a map recreation task. This approach addresses the underlying mechanics of creation and maintenance of mental representations of space over time. It is postulated here that cognitive map decay occurs as a normal and natural process when an individual is no longer re-enforcing the spatial knowledge from direct experience/perception of the learned environment. Given that humans rely on a myriad of spatial knowledge for supporting navigation, it is not surprising that access to inaccurate cognitive maps can result in error-prone and unsuccessful navigation behaviors. Previous work has demonstrated that older adults have significant difficulties in the process of forming cognitive maps due to the combination of age-related change and degradation of spatial abilities [6–8]. This knowledge motivated the current paradigm used to assess decay after forming an accurate baseline, which is meant to circumvent any formation difficulties that may otherwise have arisen. Age-related losses have also been identified in general memory structures [9–11] further impacting the storage and maintenance of spatial information. The storage of cognitive map information may also undergo losses in accuracy due to limitations of spatial memory associated with aging [12]. Considering this prior research in aggregate, a key prediction of the present work is that spatial memory decay will occur at a greater magnitude for older adults as compared to their younger counterparts, due to age-related difficulties in maintaining and accessing cognitive maps, in conjunction with known memory storage limitations.

The typical spatial cognition approach for studying cognitive maps follows a procedure where participants learn an environment and are only tested once, immediately after learning, without any intervening delay. A problem with this approach is that it only measures a 'snapshot' in time, when the representation is least likely to be contaminated by any other intervening factors. As a result, this one-time, immediate testing paradigm cannot speak to what happens to the cognitive map (or any spatial knowledge representation) with multiple testing probes performed over time. While there is a dearth of extant literature investigating the decay functions of learned spatial knowledge between younger and older adult populations, there is an abundance of research investigating memory decay (retention/forgetting functions) with other types of memory based on college-aged populations. For instance, a comprehensive review by Rubin and Wenzel (1996), compiled, transformed, and analyzed retention functions for word recognition and free recall from 210 published data sets representing a large body of literature over many years [13]. In their work, they fit each data set to over 100 different mathematical functions. In most cases, the best fit was determined by the time scale. For example, linear trends tended to be more significant in extremely short time intervals (seconds to minutes of delay). By contrast, logarithmic trends were consistently well fit for most time intervals and were the preferred trend of the authors. Logarithmic trends also showed some of the highest significance values for the time intervals over days and weeks, which is the time interval emphasized in the current research. While effects of age were not fully examined in the Rubin and Wenzel 1996 review, memory impairment was discussed briefly. The conclusions were that the presence of memory impairment affected the overall magnitude of forgetting, but loss functions were still the same as with non-impairment. It is possible that older adults, with memory impairment due to age related changes, could demonstrate similar logarithmic trends of memory decay.

In order to characterize the decay process, the present study employed a methodological paradigm which tested peoples spatial knowledge at delayed (1-day and 1-week) time intervals. Critical to this approach, all participants formed accurate baseline cognitive maps from the onset. Thus, results from the time-delayed testing measures only represent the decline of that information over time while factoring out possible interference introduced from age-related inaccuracies in cognitive map formation. Performance comparisons were made between each of the testing intervals for map sketching and pointing trials. An important parameter of the methodological design used here was to provide the opportunity for equivalent baseline spatial knowledge in order to avoid individual differences due to differential spatial learning and cognitive map development abilities. Unlike traditional longitudinal research which focuses on months or years of time, this methodological paradigm emphasizes spatial memory over shorter, more susceptible intervals in the days and weeks after the spatial information is formed [13].

This work employed immersive virtual reality (VR) driving simulation in order to facilitate large-scale outdoor navigation. The use of virtual reality with older adult populations is far less prevalent than with younger adults. Additionally, VR research involving elder populations frequently does not use head-mounted displays and immersive virtual reality, as is done here. Instead, research with aging typically makes use of more readily available and easier to use desktop monitors. The use of a more modern VR solution affords advantages over these simpler approaches, including greater realism

and improved immersion, while allowing for increased integration with various hardware (such as a realistic driving simulator as is used here). Previous work by our group has evaluated the efficacy and usability of the immersive VR driving simulator used in this research, with both younger and older adults [14]. That work found performance in the virtual simulation to match real-world data for known 'problem areas' of older adult drivers, such as correctly yielding at intersections, accurate speed maintenance, and degraded braking reaction times.

2   Method

Participants. Twenty participants completed the study, evenly split between two age groups. The older adult age group consisted of ten people (6 female), ages 60–80 (M = 70.3, SD = 7.6). The younger adult age group included ten people (5 female), ages 18–36 (M = 22.1, SD = 4.7). Due to the sample size, the power to detect small effects is limited. Educational experience was closely matched between age groups, averaging just under 16 years for both groups (with 16 representing an undergraduate degree). Prior to starting the experiment, the older adult group completed the Montreal Cognitive Assessment, a common instrument in aging research for assessing cognitive impairment (all participants scored equal to or greater than 26, indicating no abnormal cognitive impairment) [15]. This research was approved by the University of Maine's local ethics committee and written informed consent was obtained from all participants.

Apparatus. This study employs a novel use of VR as a research tool for evaluating spatial behaviors of older adult populations. VR motion sickness is a concern for younger adults and is further exacerbated with age [16]; thus, this system was designed to help alleviate simulation sickness through careful matching of real and virtual visual expectations, choice of textures/models, and superior clarity/refresh rate of the display (further details on, and evaluation of, the driving simulator can be found in [14]). The HMD used for this study was an nVisor SX111, from NVis inc. The SX111 has a 111° field of view, providing a wide area for the driver to see in their peripheral vision. The SX111 also provides two individually driven stereoscopic displays, with separate graphics processing for each eye, rendering images at a display resolution of 1280 × 1024 per eye. The physics software was delivered by the Unreal Engine programming environment. In order to achieve greater immersion and provide a complete residential environment, 3D models of homes, businesses, landmarks, etc., were created in-lab using the Maya 3D modeling software, a product of the Autodesk Company. The driving simulator was constructed in-house using the driver's seat from a Ford Crown Victoria and the steering wheel and pedals from a disassembled Playseat racing seat. The height of the base platform and roll-cage style stabilization bars were designed in-house to maximize safety, given the intended use of the driving simulator with an older adult population. Figure 1 below shows the driving simulator used for this research.

Fig. 1. Picture of the driving simulator.

The main driving course for this experiment was based on a two box grid system in the form of a figure eight. Participants learned four major landmarks within this map (playground, gas station, water tower, and corner store). An additional home location (house designated as the starting location) was placed in the environment, and each participant began their learning phase from this home location. See Fig. 2 below for a top down view of the road network and placement of landmarks.
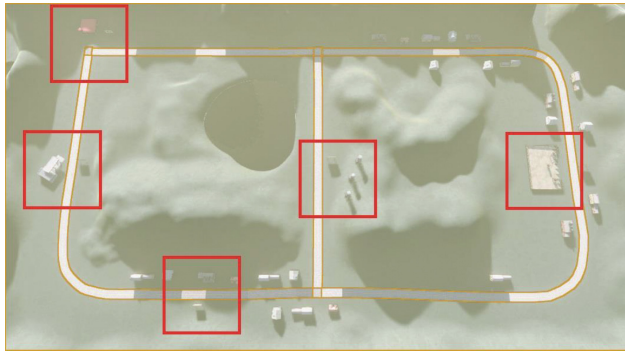

Fig. 2. Top-down view of the road grid and landmark placement. Yellow outlines represent the roads and the red squares indicate landmark locations. (Color figure online)

Design and Procedure. Participants began the experiment with a 5-minute practice phase. During this period, they practiced on a simplified course where they could adjust to the driving simulator apparatus as well as the immersive virtual reality experience. Upon completion of practice, a criterion test was given to ensure that participants were both comfortable and accurate in using the system. For this test, they had to maintain a speed between 10 and 15 mph while weaving back and forth between 6 cones, which were placed a fixed distance apart in the middle of the virtual road. After negotiating

the cones, they then had to correctly observe a stop sign. This criterion test was designed to assess the participant's ability to accurately use/operate the driving simulator while managing acceleration, speed, vehicle control, and breaking behaviors, as these were all factors of interest that were subsequently evaluated in the experimental trials. No participants failed this criterion test (no cones were hit and all participants stopped before the sign).

Once participants met criterion in the practice course, they moved on to the experimental driving course. During the learning period, participants were allowed free and unlimited exploration of the environment. They were notified once they had explored the entire environment at least once, but were encouraged to continue their exploration until they self-assessed as having a comfortable level of spatial knowledge of the environment as a whole, including the position of all landmarks. After completing free exploration and removing the head mounted display, participants were required to draw a top-down map of the environment, including roads and placement of the four landmarks in the proper locations on the map. The home location (i.e., the starting point during the free exploration phase) was provided as a reference, see Fig. 3 for an image of the sheet used for map recreation.
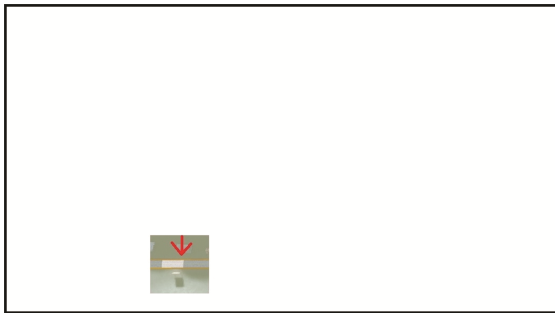
Please sketch the map including roads and landmarks.

Fig. 3. Map sketching sheet given to participants for re-creation of the learned environment. The home location (starting point) was given as a reference.

If participants were unable to correctly re-create the learned environment, they returned to the driving simulator for an additional learning phase. Participants repeated this cycle of learning followed by sketch map completion testing until they had created an accurate map of the learning environment. The map recreation criterion was determined by comparing the drawn maps to that of the correct physical map of the space being learned (landmark and road layout placement). Specifications for this criterion were based on placement within a 10% threshold of the overall map-sketching space. Accurate landmark placement and road layouts would thus need to have been within a 0.6×1.0 in. rectangular region centered on the correct landmark location or road intersection/turning point for the 6×10 in. drawing space of the sheet given (shown in Fig. 3). This sketch map served as a reflection of the accuracy of participants' internal

representation, i.e. their cognitive map. The amount of repetitions of learning phases needed to complete an accurate sketch map was also collected for each participant.

Once a correct map was created, participants performed several pointing tasks. These tasks were done on paper, using a blank version of the sketch map sheet where only the boundaries of the learned space and starting landmark were provided (no internal connectivity or landmark locations were given). The first pointing task involved egocentric pointing, where participants were asked to imagine that they were at the home location facing their starting direction and to draw a line to the angle of each landmark. Egocentric pointing was done using separate sheets for each landmark. The reasoning for using separate sheets for this task was to discourage further inter-landmark learning and to mimic as closely as possible the procedure for the subsequent time-delayed take-home testing. Next, participants performed an allocentric pointing task, which is a spatial task that is known to be difficult for older adults [17]. In this task, each participant was given judgments of relative direction (JRDs) whereby they had to point to a landmark while imagining facing another landmark. For example, a participant may first be instructed to imagine that they are standing at the home location and facing the gas station. Now that they have this imagined position and facing direction in mind, they would then be requested to point to the store. JRD trials covered all combinations of pointing pairs between landmarks in aggregate. The in-lab map sketching, egocentric pointing, and allocentric pointing tasks served as a baseline for comparison to the time delayed testing that was subsequently performed one day and one week later.

Upon completing the learning and testing phases, each participant was given two packets to take home with them. Each packet contained a set of materials that matched the same tasks they did immediately upon completing the learning phase. The packet included the same mostly blank pages, as used for in-lab testing, for sketching their map, egocentric pointing, and allocentric pointing trials. Participants were then instructed to wait until approximately the same time on the following day to complete the first packet and one week from then at approximately the same time to complete the second packet. At those designated times, they were requested to open the packet and to complete all of the tasks it contained, thereby following the same procedure as was done in the lab. Each packet also included a stamped and self-addressed envelope in which all materials were placed and mailed back to the lab upon completion. The testing packets were labeled with the participant numbers and designated dates for completion. Participants were instructed to complete the packets on the specific dates, but asked to report if there were any deviations from the scheduled times/dates. All packets were completed on schedule as self-reported by the participants.

Once received, sketch maps and pointing trials were analyzed for each time interval. The sketch maps were analyzed by comparing the participant's creation of the road layout and landmark placement (representing specific x-y coordinate points on the map) against the correct map. The analysis was accomplished by using a sketch map analyzing software named the *Gardony Map Drawing Analyzer* [18] developed based on bi-dimensional regression analysis [19, 20]. This process uses the sketch map road layout and landmark points to form polygons that are then compared for translation, rotation, and scaling differences through a least squares method. Several variables are created from the output of this process, including: (1) Scale: a measure of size differences

between response polygons and the ideal polygon, (2) Theta: rotational differences between the response and ideal polygon, and (3) Distortion Index (DI): a variable that represents the overall accuracy of the polygons taken from the participants' sketch maps and irrespective of translation, rotation, and scale [12]. The distortion index values are within a possible range from 0 to 100, with 0 representing a perfect placement of layout or landmark points. To score the egocentric and allocentric data, responses for each trial were physically measured on the pages using a protractor. These values were then directly compared to the correct values for each trial in order to calculate signed error and absolute error. Signed error represents directional bias of responses and absolute error indicates the overall magnitude of the response errors. Learning times and learning counts, the number of learning phases it required a participant to form an accurate baseline sketch map, were determined from the driving logs collected during the experiment. Bi-dimensional regression variables, all pointing trials, and all learning data were analyzed using a mixed model ANOVA with age group as a between subject factor and time interval as a within subject factor.

3 Results

Elimination of Outliers. Outliers were identified based on data points that were 2.5 standard deviations above the mean for each given time interval and age group combination. This resulted in 3.6% of the data being replaced by the respective mean from the condition where the outlier was calculated.

Learning Data. Data collected from the learning phases included learning times and a count of how many learning phases were required for a participant to meet criterion, assessed by the ability to create an accurate baseline sketch map (suggesting development of an accurate underlying cognitive map). Older adult learning times averaged about 12.3 min (M = 735.0 s, SD = 241.5 s) and younger adults took about 5.5 min to learn the environment (M = 329.5 s, SD = 62.7 s). An independent samples T-test comparing the learning times between the two age groups showed significant differences $t(18) = 4.392$, $p = 0.001$. This finding indicates that older adults took consistently longer to learn the environments; approximately twice as much time as younger adults. At most, it took participants two learning phases to form accurate baseline sketch maps. There was no difference between age groups for this measure, as both groups averaged 1.3 learning phases per person.

Sketch Map Analysis: Landmarks. Each of the participants' sketch maps contained the locations of the 5 landmarks learned during the in-lab driving session (Home, Gas Station, CVS, Water Tower, and Playground). The polygon formed between these points was run through the bi-dimensional regression analysis to calculate the differences in scale, theta (rotation), and overall distortion (DI). Distortion index value means for both age groups are shown in Fig. 4 below.
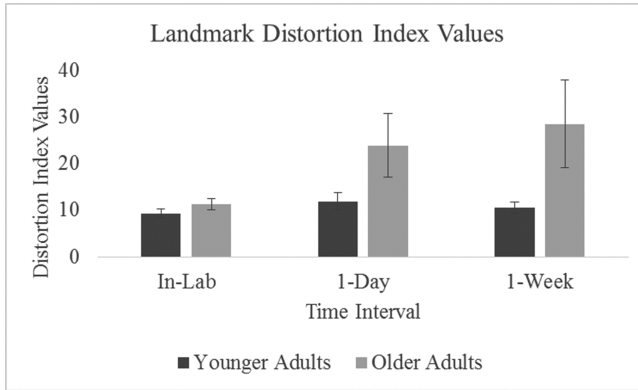
Fig. 4. Mean distortion index values for younger and older adult landmark placement with standard error shown.

Distortion Index values are perhaps the best measure of sketch map accuracy as they represent the overall error between user response and the ideal landmark placement. The results for the ANOVA on distortion index values revealed significant age group differences [$F(1,18) = 7.30$, $p = 0.009$, *partial* $\eta^2 = 0.119$]. Reflecting that the older adult sketch maps are less accurate than those of the younger adults. Testing time interval was not significant for older adults [$F(2,9) = 1.75$, $p = 0.192$, *partial* $\eta^2 = 0.115$] or for younger adults [$F(2,9) = 0.83$, $p = 0.449$, *partial* $\eta^2 = 0.064$]. No significant interaction was observed, $p > 0.250$. Older adults' landmark placements were consistently worse than younger adults. There were numerical differences between the distortion index values at the two delayed time intervals (1-day and 1-week) compared to the immediate in-lab testing period; however, these differences did not reach significance.

All age group and time interval means and standard deviations for scale and theta can be found in Table 1. ANOVA results for the scale measure did not reach significance for age group [$F(1,18) = 3.95$, $p = 0.053$, *partial* $\eta^2 = 0.076$]. Time interval for the older adults [$F(2,9) = 2.89$, $p = 0.075$, *partial* $\eta^2 = 0.194$] and younger adults [$F(2,9) = 0.72$, $p = 0.498$, *partial* $\eta^2 = 0.056$] were also not found to be significant. The interaction between age group and time interval was not significant, $p > 0.150$. As can be seen from the omnibus F-tests, the age group and time interval differences for older adults were very close to significance, indicating a clear numeric trend for differences between the sketch maps of older adults and younger adults as well as decline in scale accuracy of the cognitive maps of older adults over time. ANOVA results for the theta variable revealed significant age group differences [$F(1,18) = 9.09$, $p = 0.004$, *partial* $\eta^2 = 0.159$], time interval effect for older adults [$F(2,9) = 6.73$, $p = 0.005$, *partial* $\eta^2 = 0.359$], and the interaction between age group and time interval [$F(3,18) = 6.78$, $p = 0.003$, *partial* $\eta^2 = 0.220$]. These results show that older adults exhibit consistently more rotational offset within their sketch maps than younger adults and that this rotational error increased as a function of testing time, i.e. the interval from initial testing after meeting the criterion baseline to the subsequent testing at 1-day and 1-week delays. By contrast, time interval was not found to be significant for younger adults [$F(2,9) = 0.13$, $p = 0.877$, *partial*

$\eta^2 = 0.011$]. The lack of significance of time interval for the younger adults, indicates that this demographic did not experience any statistically measurable accruement of angular error within their sketch maps over time. The rotational error within the sketch maps ranged from 2° to 20° for older adults, and only from about 3° to 4° for younger adults (See Table 1 for all means and standard deviations).

Table 1. Displays the scale and theta averages and standard deviations for younger and older adults across the three time intervals for landmark placement.

Time	Scale		Theta (degrees)	
	Older	Younger	Older	Younger
In-lab	0.96 (0.13)	0.95 (0.11)	2.4 (1.8)	3.4 (2.3)
1-day	0.72 (0.31)	0.91 (0.06)	20.5 (19.9)	4.5 (4.0)
1-week	0.87 (0.27)	0.93 (0.04)	10.0 (12.7)	4.0 (2.7)

Sketch Map Analysis: Road Layout.   Key points, including road intersections and road turn/corner placements, were used to form the road layout polygon. The layout errors of participant sketch maps were analyzed using the same bi-dimensional regression method as was used with the landmark placement. Distortion index value means for both age groups can be found in Fig. 5 below.
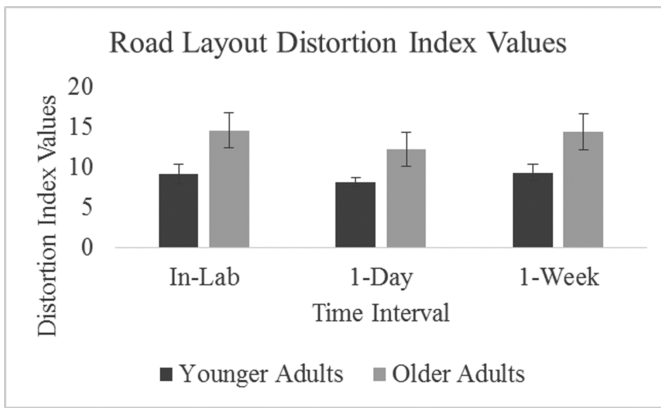

Fig. 5. Mean distortion index values for younger and older adult road layout recreation, with standard error bars depicted.

Distortion index values for the road layout were entered into the same omnibus ANOVA as was done with the landmark distortion values. Results showed a significant difference between the two age groups [$F(1,18) = 13.64, p = 0.001, partial\ \eta^2 = 0.221$]. Time interval effects were not significant for the older adults [$F(2,9) = 0.26, p = 0.777, partial\ \eta^2 = 0.021$] or younger adults [$F(2,9) = 0.42, p = 0.661, partial\ \eta^2 = 0.034$]. Likewise, the age group by time interval interaction was not significant, $p > 0.300$. These results indicate that road layout creation by older adults was reliably worse than those created by younger adults but that accuracy did not further decline over the temporal

duration of testing. We interpret this age group difference as reflecting a general age effect for sketch map accuracy. Overall however, road layout was extremely accurate for both groups. This outcome indicates that the layout information (represented by the road network) was a component of the cognitive map that is stable over time, albeit slightly degraded as a general function of spatial abilities affected by the aging process.

Means and standard deviations for scale and theta of the road layouts are shown in Table 2 below. Results from the ANOVA on the scale variable were not significant for age group [$F(1,18) = 0.47$, $p = 0.496$, *partial* $\eta^2 = 0.010$], older adult time interval [$F(2,9) = 0.64$, $p = 0.535$, *partial* $\eta^2 = 0.051$], or younger adult time interval [$F(2,9) = 0.08$, $p = 0.928$, *partial* $\eta^2 = 0.006$]. In addition, no significant age by time interval interaction was found, $p > 0.150$. These findings suggest that there were no consistent differences in scale accuracy between older and younger adult sketch maps across the testing times used in this study. ANOVA results for the theta variable did reveal a significant effect of age group [$F(1,18) = 6.10$, $p = 0.017$, *partial* $\eta^2 = 0.113$], but no significance of time interval as a function of age, older adults [$F(2,9) = 1.38$, $p = 0.270$, *partial* $\eta^2 = 0.103$] and younger adults [$F(2,9) = 0.43$, $p = 0.656$, *partial* $\eta^2 = 0.035$]. The interaction between age group and time interval was not significant, $p > 0.300$. This outcome indicates that there was reliably more rotation of sketch maps for older adults than that of their younger counterparts. Overall however, scale of the re-created layout and rotational errors (theta) were very low. This outcome was most likely due to the simple layout employed to allow for an environment that older adults could readily learn.

Table 2. Displays the scale and theta averages and standard deviations for younger and older adults across the three time intervals for road layout.

Time	Scale		Theta (degrees)	
	Older	Younger	Older	Younger
In-lab	0.88 (0.12)	0.86 (0.07)	1.0 (0.6)	0.4 (0.4)
1-day	0.87 (0.16)	0.87 (0.04)	1.9 (3.0)	0.6 (0.5)
1-week	0.94 (0.19)	0.87 (0.04)	1.5 (1.5)	0.6 (0.6)

Pointing Trials: Egocentric. Participants completed egocentric pointing trials to each of the landmarks learned. Egocentric pointing reflects the accuracy of the underlying cognitive map as relates to the maintenance of self-object relations. The difference between the response angle and the actual angle was calculated to evaluate bias (signed error of pointing) and the absolute value of those values was used to determine error magnitude. Directional bias within the egocentric pointing task was analyzed using the same ANOVA model as was used with the previous measures. No significance was found for any of the measures and overall there was no left/right bias in the pointing judgments. The calculated absolute angle error averages and standard errors for both age groups across the three time intervals are shown in Fig. 6. ANOVA results for egocentric pointing revealed significant differences between the two age groups [$F(1,18) = 18.24$, $p < 0.001$, *partial* $\eta^2 = 0.072$]. No significant effect for egocentric pointing accuracy was found as a function of testing time interval: older adults [$F(1,9) = 1.35$, $p = 0.264$, *partial* $\eta^2 = 0.024$] and younger adults [$F(2,9) = 0.49$,

$p = 0.614$, *partial* $\eta^2 = 0.009$]. No significant age group by time interval interaction was observed, $p > 0.150$. These findings indicate that older adults show greater error in egocentric pointing judgments than younger adults, but this error did not reliably increase as a function of time interval over which the judgments were made.
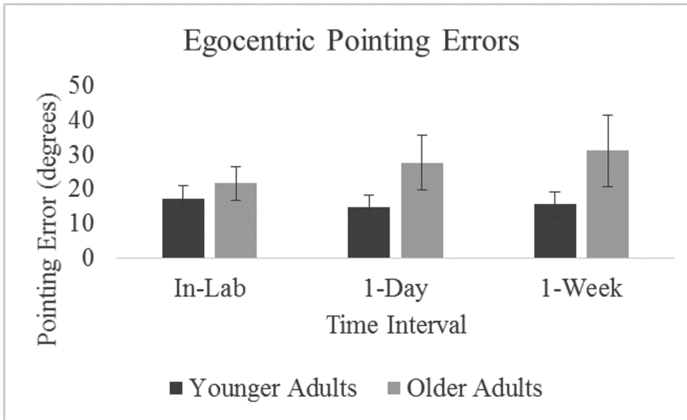

Fig. 6. Average egocentric pointing errors for both age groups across the three time intervals with standard error bars.

Pointing Trials: Allocentric. Participants completed allocentric pointing trials at each testing time interval for all pairs of landmark locations. These trials had participants imagine standing at one location, facing one landmark, and then pointing to another. Allocentric pointing performance reflects the knowledge of object-to-object relations that were stored and maintained in the cognitive map. Allocentric pointing error was calculated between the response and correct angle. Directional bias within the pointing task was analyzed using the same ANOVA Model as above, with no significant effects found for any of the factors (all p's > 0.05). ANOVA results for the absolute allocentric pointing errors showed significant differences between age groups [$F(1,18) = 94.54$, $p < 0.001$, *partial* $\eta^2 = 0.117$]. However, there were no reliable differences observed between the testing time intervals for older adults [$F(2,9) = 2.10$, $p = 0.124$, *partial* $\eta^2 = 0.012$] or for younger adults [$F(2,9) = 1.46$, $p = 0.234$, *partial* $\eta^2 = 0.008$]. Similarly, no significant interaction between age group and time interval was found, $p > 0.100$. These results suggest that older adults were consistently worse than younger adults for allocentric pointing accuracy, regardless of the testing time interval that the judgments were made. This finding is not surprising, as previous research has shown that older adults have a more difficult time than their younger peers on allocentric tasks [12, 17]. Means and standard deviations of the allocentric pointing trials can be found in Table 3 below.

Table 3. Average allocentric pointing errors and standard deviations for both age groups across the three time intervals.

Allocentric pointing data (in degrees)			
Age group	Time interval	Mean	Standard deviation
Older	in-lab	59.52	41.19
Older	1-day	63.10	41.57
Older	1-week	52.42	40.47
Younger	In-lab	32.14	20.86
Younger	1-day	35.78	20.24
Younger	1-week	36.36	21.13

4   Discussion

The present research was designed to evaluate differences that manifest in cognitive map decay between older and younger adults, and to characterize the decay function through several measures of spatial behavior. This was accomplished through examining differences in sketch maps (physical representations of cognitive maps) and performance on egocentric and allocentric pointing trials between younger and older adults over multiple time periods. The methodological paradigm was designed in a way that all tasks were done after forming a highly accurate baseline. Given that previous research has found that cognitive map formation is impacted by age, it was postulated here that the maintenance of the same spatial knowledge would also be affected by age. This prediction was partially supported by the outcomes of this study as older adult showed reduced spatial knowledge as compared to younger adults on the same tasks. The data clearly reflect a trend that older adults exhibit a greater decay in spatial knowledge of the learned environment over time as compared to younger adults.

Results also showed that it took older adults about twice as long to learn the environments than their younger counterparts. The complexity of the environment was designed to be challenging for the older adults but in this study, we emphasized landmark configuration complexity over road network configuration complexity. This design choice was made to ensure that we could collect a robust data set for the egocentric and allocentric pointing judgments, which relied more on knowledge of landmark configuration than road network complexity. The decision to allow all participants time to form an accurate baseline cognitive map is a unique component of the current methodological approach that was implemented in order to ensure consistency between individuals during the formation process. If a fixed time limit had been imposed during the learning phase, it would not have been possible to ensure that all participants were operating from an accurate baseline representation. As a result, the cognitive maps of the older adults may have suffered from increased formation error compared to the younger participants, which would have compromised the efficacy of comparing the decay functions between groups. In sum, guaranteeing an accurate initial baseline provides a robust technique that supports strong statistical efficacy for detecting any changes in cognitive map accuracy over the subsequent time-delayed testing intervals for each task (map sketching, egocentric pointing, and allocentric pointing). With this design, any changes in

performance during delayed testing can be attributable to the decay process, rather than to problems in cognitive map formation. Evidence for forming this accurate baseline for the older adults can be observed in Figs. 4 and 6, where the in-lab performance (tested spatial knowledge) nearly matched that of the younger adult group.

Conducting the bi-dimensional regression analysis on the sketch maps elucidated differences that exist in the underlying cognitive maps between older and younger adults. The cognitive maps of older adults were shown to be more susceptible to errors and overall distortion of landmark placements and road layouts as compared to younger adults. The magnitude of decline for older adults was specifically attributed to age-related effects on the decay process, given that all participants were required to develop their initial cognitive maps to accurate baselines. Increased distortion for older adult cognitive maps was evident from both landmark placement and road layout accuracy in their physical map recreations. Many of the same underlying mental structures for memory are used for storage and access of cognitive maps. As such, it is reasonable to expect that the methodological paradigm employed in the current work could also be applied to other spatial tasks that may change as a function of the aging process.

The loss of cognitive map accuracy may reduce the ability for older adults to successfully navigate using this internal spatial information. As previous research has shown, cognitive maps are key to accurate navigation and older adults clearly display losses in this long-term store of spatial knowledge after accurate learning of the environment, as evidenced by the current results. Other types of memory formation have demonstrated decay of information over time as following a logarithmic trend. In the current study, there were no reliable mathematical trends in the data. However, in-line with previous findings, the closest predictive trend from our data was a logarithmic function. Due to the high standard deviations and small sample size, the effect of time interval for older adults may have only been numeric, but the large absolute difference between the distortion values from the immediate time interval testing (11.2) and the combined average of the two time delayed testing intervals (32.2) is notable. The performance differences on map recreation between immediate and delayed sketch maps provides an indication that decay is occurring in the older adults' cognitive maps as time passes.

The decay of cognitive maps had a slightly different effect on other measures of interest related to physical map recreation. For instance, reliable differences in scale were not observed but significant differences in rotational errors were evident. These results suggest that older adults accurately maintain the distance relations between landmarks within their cognitive maps in a similar manner as younger adults. Likewise, neither younger nor older adults exhibited reliable compression or expansion effects for the spatial relations of the stored landmark knowledge over time. Rotational errors for landmark placements and road layouts were found to be significantly greater as a function of age during recreation, indicating that the cognitive maps of older adults are more susceptible to distortions in these factors as compared to their younger counterparts. The amount of rotational error also increased significantly over the time intervals tested for older adults. This outcome indicates that the cognitive maps of older adults are more susceptible to rotational error, but that the overall inter-landmark relations are maintained. From a practical standpoint, imagine placing a physical map onto a table lined

up with true north. If you then rotate the map, the angles of the individual landmarks as they relate to the global environment are now incorrect, but within the map the landmark-to-landmark distances and angles are stable. The current data suggests that the same overall rotation of a cognitive map would lead to navigational difficulties for older adults.

Egocentric pointing data also revealed strong age group differences as well as numeric differences in error as a function of time delayed testing. Significantly worse pointing responses for older adults represents inaccuracies of landmark placement within the stored cognitive maps as compared to younger adults. These results further explain the significance of rotational errors within the cognitive maps demonstrated from the bi-dimensional theta values. As mentioned above, older adult cognitive maps seem to reflect greater rotational error of the stored landmark locations. These egocentric pointing errors reflect the same increase in rotation of landmark relations for older adults as were observed in the bi-dimensional regression analysis. Previous research has found that egocentric spatial abilities tend to be preserved for older adults as compared to allocentric pointing [4, 5]. However, some recent work by Giudice and colleagues has found exceptions, demonstrating declines in egocentric performance for older adults after learning multi-target haptic arrays [12]. The current results support the Giudice et al. findings in the haptic domain and extend the finding of age-related egocentric deficits between older and younger participant groups after visual learning of multi-target layouts. High variability within the egocentric pointing errors certainly contributed to the lack of significance observed for time interval; however, the in-lab errors averaged about 21° and the two time-delayed errors averaged about 30°. This gap between immediate and time delayed errors reflects a strong numeric pattern suggesting a temporal effect on remembered landmark locations. As with the distortion values, no mathematical trend was significant for egocentric pointing errors from older adults over time. However, the logarithmic function was the closest to significant as a predictor for pointing errors.

There were however, greater errors for allocentric pointing for older adults as compared to their egocentric performance. In this sense, older adults performed better with the egocentric task than the allocentric trials, but their egocentric errors were still significantly greater than those exhibited by the younger adults. Allocentric pointing also showed age group differences with older adults averaging about 58° of error and younger adults about 35°. Recent work by Giudice et al. (2017) also found significant differences between age groups for allocentric pointing [12]. The means for the older adult group (34°) and younger adult group (18°) for that work were however on a lower scale than the errors found here. Overall, the errors for this allocentric pointing task showed that both age groups exhibited relatively poor performance, with even the younger adults averaging about 35° of error and the older adults showing highly variable performance between time intervals (see Table 3 for exact means). This could be due to the method of execution for the allocentric trials. In order to accommodate the time delayed testing, the pointing trials were done on paper and this technique may have introduced increased allocentric errors for both age groups.

In conclusion, the current study elucidated differences in remembered cognitive map accuracy between younger and older adults. The results demonstrated that older adults were disadvantaged compared to younger adults, including a pattern of performance

decline for older adults across the temporally delayed testing intervals of one-day and one-week. The methodological paradigm used in this research to evaluate cognitive map decay lays the groundwork for additional research on spatial decay functions. The characterization of the decay function will be further examined with methodological changes made to strengthen the mathematical trend analysis (including larger sample sizes and additional time interval testing).

References

1. Bennett, A.T.: Do animals have cognitive maps? J. Exp. Biol. **199**(1), 219–224 (1996)
2. Golledge, R.G.: Wayfinding Behavior: Cognitive Mapping and Other Spatial Processes. JHU Press, Baltimore (1999)
3. Tolman, E.C.: Cognitive maps in rats and men. Psychol. Rev. **55**(4), 189–208 (1948)
4. Klencklen, G., Després, O., Dufour, A.: What do we know about aging and spatial cognition? Reviews and perspectives. Ageing Res. Rev. **11**(1), 123–135 (2012)
5. Moffat, S.D.: Aging and spatial navigation: what do we know and where do we go? Neuropsychol. Rev. **19**(4), 478–489 (2009)
6. Harris, M.A., Wolbers, T.: Ageing effects on path integration and landmark navigation. Hippocampus **22**(8), 1770–1780 (2012)
7. Head, D., Isom, M.: Age effects on wayfinding and route learning skills. Behav. Brain Res. **209**(1), 49–58 (2010)
8. Iaria, G., et al.: Age differences in the formation and use of cognitive maps. Behav. Brain Res. **196**(2), 187–191 (2009)
9. Park, D.C.: The basic mechanisms accounting for age-related decline in cognitive function. In: Park, D.C., Schwarz, N. (eds.) Cognitive Aging: A Primer, vol. 11, pp. 3–19. Psychology Press, Philadelphia (2000)
10. Park, D.C.: Cognitive Aging: A Primer. Psychology Press, Philadelphia (2000)
11. Park, D.C., et al.: Models of visuospatial and verbal memory across the adult life span. Psychol. Aging **17**(2), 299–320 (2002)
12. Giudice, N.A., et al.: Spatial updating of haptic arrays across the lifespan. Exp. Aging Res. **43**, 274–290 (2017)
13. Rubin, D.C., Wenzel, A.E.: One hundred years of forgetting: a quantitative description of retention. Psychol. Rev. **103**(4), 734 (1996)
14. Bennett, C.R., Corey, R.R., Giudice, U., Giudice, N.A.: Immersive virtual reality simulation as a tool for aging and driving research. In: Zhou, J., Salvendy, G. (eds.) ITAP 2016. LNCS, vol. 9755, pp. 377–385. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-39949-2_36
15. Nasreddine, Z.S., et al.: The montreal cognitive assessment, MoCA: a brief screening tool for mild cognitive impairment. J. Am. Geriatr. Soc. **53**(4), 695–699 (2005)
16. Brooks, J.O., et al.: Simulator sickness during driving simulation studies. Accid. Anal. Prev. **42**(3), 788–796 (2010)

17. Antonova, E., et al.: Age-related neural activity during allocentric spatial memory. Memory **17**(2), 125–143 (2009)
18. Gardony, A.L., Taylor, H.A., Brunye, T.T.: Gardony map drawing analyzer: software for quantitative analysis of sketch maps. Behav. Res. Methods **48**(1), 151–177 (2016)
19. Tobler, W.R.: Bidimensional regression. Geogr. Anal. **26**(3), 187–212 (1994)
20. Friedman, A., Kohler, B.: Bidimensional regression: assessing the configural similarity and accuracy of cognitive maps and other two-dimensional data sets. Psychol. Methods **8**(4), 468 (2003)