Psychology and Aging

Age Differences in Spatial Memory for Mediated Environments

Lauren L. Richmond, Jesse Q. Sargent, Shaney Flores, and Jeffrey M. Zacks

Online First Publication, August 20, 2018. http://dx.doi.org/10.1037/pag0000286

American Psychological Association

Psychology and Aging

0882-7974/18/$12.00 http://dx.doi.org/10.1037/pag0000286

Age Differences in Spatial Memory for Mediated Environments

Lauren L. Richmond
Washington University in St. Louis

Jesse Q. Sargent
Francis Marion University

Shaney Flores and Jeffrey M. Zacks
Washington University in St. Louis

Compared with younger adults, older adults have more difficulty with navigation and spatial memory in both familiar and unfamiliar domains. However, the cognitive mechanisms underlying these effects have been little explored. We examined three potential factors: (a) use of and coordination across spatial reference frames, (b) nonspatial cognitive abilities, and (c) the ability to segment a route into effective chunks. In two experiments, healthy young and older adults watched videos of navigation in a novel environment and had to remember the placement of landmarks along the route. Participants completed three spatial memory tasks—a virtual pointing task, a distance estimation task, and sketch map drawing—for each route. The pointing task depends on updating and accessing the updated egocentric reference frame relative to other frames. Map drawing may rely more on environment-centered processing. The distance estimation task could be solved using either frame of reference. Last, participants segmented each route. In a separate session, working memory, processing speed, and verbal memory were assessed. Older adults performed less well on all spatial tasks compared with younger adults; aging had a stronger negative effect on pointing performance. This may point to impairments in older adults' ability to update and coordinate information across reference frames. Performance on all spatial tasks was predicted by nonspatial task performance. Segmentation did not predict spatial memory. These results underline the importance of situating age differences in navigation in the context of basic transformations of spatial reference frames, and also in the context of nonspatial cognitive abilities.

Keywords: cognitive aging, individual differences, spatial memory, spatial navigation

Supplemental materials: http://dx.doi.org/10.1037/pag0000286.supp

Spatial memory and spatial navigation skills are essential for effective everyday functioning. For example, someone who struggles to remember where medications are stored will have trouble with medication administration (Lawton & Brody, 1969), and someone who struggles to navigate to the pharmacy will be at risk for becoming lost or disoriented (Burns, 1999) should they try to complete the pharmacy trip on their own. The former might be best described as a spatial memory challenge, whereas the latter might be better characterized as more specifically taxing spatial navigation. Both spatial navigation and spatial memory skills are known to be degraded in older adults, and can lead to loss of independence and increased burden on caregivers to assist with completion of activities of daily living (Gold, 2012; Lawton & Brody, 1969). To better understand these deficits, the current study asks whether older adults have problems with specific reference frames or reference frame transformations, and whether age-related spatial deficits are related to deficits in other cognitive domains including working memory, verbal memory, processing speed, as well as spatial and temporal segmentation ability.

Age Differences in Spatial Reference Frame Processing and Use

Older adults are often more impaired on tasks that tap into an environment-centered frame of reference than tasks that tap into an egocentric frame of reference (Moffat & Resnick, 2002), although this pattern is not always observed (Lemay, Bertram, & Stelmach, 2004). Older adults tend to prefer to use an egocentric navigational style rather than an environment-centered reference frame when planning a route (Rodgers, Sindone, & Moffat, 2012), and exhibit more difficulty in switching to an environment-centered navigation strategy when instructed to do so (Harris, Wiener, & Wolbers, 2012). In real-world navigation, egocentric navigation experiences need to be translated to environment-centered (allocentric) refer-

Lauren L. Richmond, Department of Psychological and Brain Sciences, Washington University in St. Louis; Jesse Q. Sargent, Department of Psychology, Francis Marion University; Shaney Flores and Jeffrey M. Zacks, Department of Psychological and Brain Sciences, Washington University in St. Louis.

This research was supported by National Institute on Aging Grant R21 AG041419, PIs Jeffrey M. Zacks and Jesse Q. Sargent. Portions of this research were presented at the 55th and 56th Annual Meetings of the Psychonomic Society.

Correspondence concerning this article should be addressed to Lauren L. Richmond, who is now at the Department of Psychology, Stony Brook University, Psychology Building B, Stony Brook, NY 11794. E-mail: lauren.richmond@stonybrook.edu

ence frames (Filimon, 2015). However, in tasks tapping spatial memory that involve little to no navigational component, the effect of different reference frames in older adults is mixed (Colombo et al., 2017). It is possible that such reference frame transformations are particularly difficult for older adults. Such differences could reflect experience-independent effects of aging or could reflect differences between older and younger cohorts in experiences with access to representations such as maps and heads-up displays on smartphones.

Spatial memory and navigation tasks usually require some degree of coordinating across egocentric and environment-centered reference frames (Zacks & Michelon, 2005). Egocentric codes must be updated as one moves or imagines moving to a new viewpoint, and as a result they are often short-lived and vulnerable to interference. For example, Wang and Brockmole (2003a, 2003b) have demonstrated that in some situations self-to-object relationships are maintained for the current environment only. When one transitions from one place to another, spatial codes for the new environment are activated (in working memory), and those for the old environment that is no longer being occupied are consequently held in less active memory states. Older adults may exhibit poorer performance on tasks that require heavier use of environment-centered reference frames *or* on tasks that require a greater number of transformations between reference frames.

Age Differences in Spatial and Nonspatial Cognition

Older adults perform more poorly spatial memory and navigation tasks in both novel and familiar environments (see Moffat, 2009 for a review). They exhibit specific deficits in planning efficient routes (Webber & Hansen, 2000), are less likely to create a mental map of an environment (e.g., Iaria, Palermo, Committeri, & Barton, 2009), and are less able to make use of navigationally relevant landmarks to guide route selection (Head & Isom, 2010; see Klencklen, Després, & Dufour, 2012 for a review). Importantly, many of the explanations that have been offered for declines in older adults' spatial memory and navigation abilities are tied to breakdowns in specific spatial processes that accompany aging. In fact, in a recent review, Klencklen and colleagues concluded that "there is a general decline in navigation abilities among the healthy elderly. . . . Rather than being a global age-related deficit, this appears to be due to age-related effects on specific components of navigation" (Klencklen et al., 2012, p. 130).

Spatial abilities have long been thought of as being separable from other cognitive abilities. Indeed, healthy young individuals vary widely in their self-reported sense of direction (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002), ability to navigate a new environment (Weisberg, Schinazi, Newcombe, Shipley, & Epstein, 2014), and mental rotation ability (Khooshabeh, Hegarty, & Shipley, 2013). These differences persist above and beyond individual differences in intelligence, processing speed, and working memory capacity (Hegarty & Waller, 2005), suggesting that spatial memory and navigation may represent a domain-specific skillset that is at least partially independent of other cognitive operations in younger adults. However, aging has been associated with a variety of negative effects on cognition outside of the spatial domain as well; namely, declines in processing speed (Salthouse, 1996), working memory capacity (Hasher & Zacks, 1988), fluid intelligence (Horn & Cattell, 1967), and attentional control (Paxton, Barch, Storandt, & Braver, 2006) have been observed in older adults. Therefore, the extent to which the deficits in spatial processing exhibited by older adults reflect domain-specific or domain-general degradation in cognitive abilities is less well understood.

Age Differences in Event Perception and Event Memory

An important component of navigation that is not spatial per se is that navigation consists of a sequence of events in time. This raises the question whether age differences in the encoding of navigation events could contribute to age differences in spatial memory for the environments experienced during those events. Studies measuring how observers segment a stream of activity into events have shown age differences and that these age differences in event segmentation are related to subsequent memory. In a number of studies using videos of actors performing everyday activities, participants were asked to press a button to indicate when they thought that one natural and meaningful unit of activity ended and another had begun. The ability to identify normative breakpoints during encoding was related to better memory for the video (Flores, Bailey, Eisenberg, & Zacks, 2017; Kurby & Zacks, 2011; Sargent et al., 2013; Zacks, Speer, Vettel, & Jacoby, 2006), and older adults generally performed less well on both event segmentation and event memory tasks than younger adults (Kurby & Zacks, 2011; Zacks et al., 2006; but see Sargent et al., 2013). A similar principle could be at play in spatial memory: it is possible that older adults as a group segment spatial arrays in a way that is less supportive of later memory than younger adults.

The Current Research

The current studies tested younger and older adults in both spatial and nonspatial cognitive tasks. In a series of two experiments, participants watched videotaped route experiences after each of which they completed three spatial memory tests that required differential involvement and manipulation of self- and environment-centered reference frames. Working memory, verbal memory, processing speed, and segmentation ability were also tested. The first experiment used stimuli that focused on the spatial properties of the environment only to provide a strong test of spatial memory in our younger and older adult samples. Experiment 2 served as a conceptual replication of Experiment 1, and also tested for effects of temporal event structure on spatial memory. In this experiment, the stimuli involved an actor performing a goal-directed activity while navigating around the environment in order. We expected that older adults' spatial memory would be poorer than younger adults' on average, and that this age-related deficit would be larger in tasks that rely more on environment-centered reference frames, or for tasks that require more transformations between reference frames. We hypothesized that nonspatial task performance would be associated with performance on spatial tasks. Last, we expected that individuals who displayed more normative segmentation of the route would also show better memory for landmark locations, similar to previous studies of event segmentation and event memory[1] (e.g., Sargent et al., 2013; Zacks et al., 2006; Zacks, Tversky, & Iyer, 2001).

Experiment 1

Method

Participants. Participants consisted of 38 younger adults (50% female, median age: 20.0, range: 18–32 years) and 38 older adults (47.4% female, median age: 72.5, range: 65–79, median years of education: 16.0, range: 12–21 years; years of education missing for 12 older adult participants). Younger adult participants were recruited through the Psychological & Brain Sciences departmental subject pool, and older adults were recruited from the St. Louis community using the Department of Psychological & Brain Sciences Older Adult participant pool and Volunteer for Health participant pool. Younger adults were compensated with either $10 per hour or one research credit per hour of participation; older adults all received $10 an hour for participation. The Washington University in St. Louis Institutional Review Board approved all procedures.

Materials.

Spatial tasks. Participants were shown videos shot by a cameraperson navigating rectangular routes through three (3) different environments (see Figure 1; videos available for viewing and download on the Open Science Framework at the following address: https://osf.io/t2vj7/). Videos were filmed from a first-person perspective using a video camera mounted on a hand held camera stabilizer. An experienced camera operator held the camera just below eye level, pointing the camera straight ahead (in the direction of travel) and walking at a typical walking pace. At the start of each video, the cameraperson stood at one corner of the rectangular route facing in the initial direction of travel, panned 90° so that the camera aimed down what would be the final leg of the rectangle, and then panned back to initial heading direction and began walking. During each video, eight to 10 landmark items were called to the participant's attention; the item name appeared on the screen and was presented verbally in a voiceover. Participants were told that they should pay attention to the landmark locations and try to remember the placement of the landmarks. After walking the entire rectangle, the cameraperson turned to face the initial heading direction, then panned back 90° to the hallway that was just walked to emphasize that the route began and ended in the same location before returning to the initial heading direction. Participants saw each video twice through before engaging in the spatial memory tests for that route. Route order was counterbalanced across subjects.

Pointing task. After viewing a given route video twice, participants viewed the route a third time to perform a virtual pointing task. During the pointing task videos, the cameraperson stopped along the route and turned 90° to face the inner wall of the rectangular route head on. The experimental software then effectively turned over control of the camera orientation to the participants and asked participants to orient the camera in the direction of hidden landmarks. In other words, participants were asked to orient the camera in the direction they would look to see the object if there weren't any walls blocking their view. Once the camera stopped, a small image of the current target landmark appeared at the top of the screen. Participants used the left and right arrow keys to change the camera orientation. Each arrow press shifted the orientation of the camera by 5 degrees (see Figure 2 for a depiction of the display as experienced by the participant, and Figure 3A for an example of a map representation of one of the routes). The maximum turning radius was 200 degrees (100° in each direction to the left and right of the original heading position). When participants believed that the camera was facing in the direction of the hidden landmark, they submitted their response by pressing the {ENTER} key. No feedback was provided. The pointing task videos stopped three times along each long leg of the rectangular routes, where each hidden landmark along the opposite long leg was probed once per stop in random order (see Figure 3A for a depiction of the correct map). Performance was measured in degrees of error from the location of the object. The landmarks were not named in the pointing task videos the way they were in the initial object location learning videos. The pointing task occurred for only the two indoor routes because all targets were visible throughout the outdoor route, so pointing to them would not have tested spatial memory. For each subject and route, we computed the median absolute pointing error to serve as the outcome of interest.

Distance estimation task. Next, participants were asked to indicate the distance between pairs of landmarks. The verbal labels for pairs of objects appeared on the screen, and participants were asked to input the distance they thought separated the two landmarks. Each possible pair along a single route leg was probed twice, such that each object appeared once on the left and once on the right of the screen (see Figure 1). Participants were told the length of the first leg of the route in both feet and meters to use as a comparator. Participants were able to input their responses in either feet or meters by indicating which they preferred to use before beginning the distance estimation task; all responses were converted to feet before analysis. These estimates were performed for all three routes. To control for individual differences in over- or underestimation, a scaled estimate rather than raw distance error scores were used (see Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006 for a similar approach). For each subject and route, we correlated the given response in feet with the correct response and then applied Fisher's z transformation to these values. The z-transformed correlation values were used as the outcome of interest.

Map drawing task. After providing distance estimates, participants were asked to draw a map of the environment and place all of the landmarks that had been called to their attention in the video on their map. They were given a blank sheet of paper and were instructed to draw a single line for the path walked by the cameraperson, to draw an arrow to indicate the direction of travel and to place an 'x' along the route to mark the location of each landmark and to label each x with the landmark name. All partic-

[1] We also predicted that transitions between different parts of space (walking through doorways, for example) would serve as a mental placeholder and encourage people to 'chunk' landmarks in memory according to these spatial cues. For example, two landmarks that were encountered in one part of the hallway before moving through a doorway were expected to be remembered as closer together than an equidistant pair of landmarks separated by a doorway. In short, hypotheses regarding spatial chunking were not supported and will not be discussed further in this paper. A comprehensive report regarding the lack of chunking observed with these materials, in these two experiments and in several others, is forthcoming.

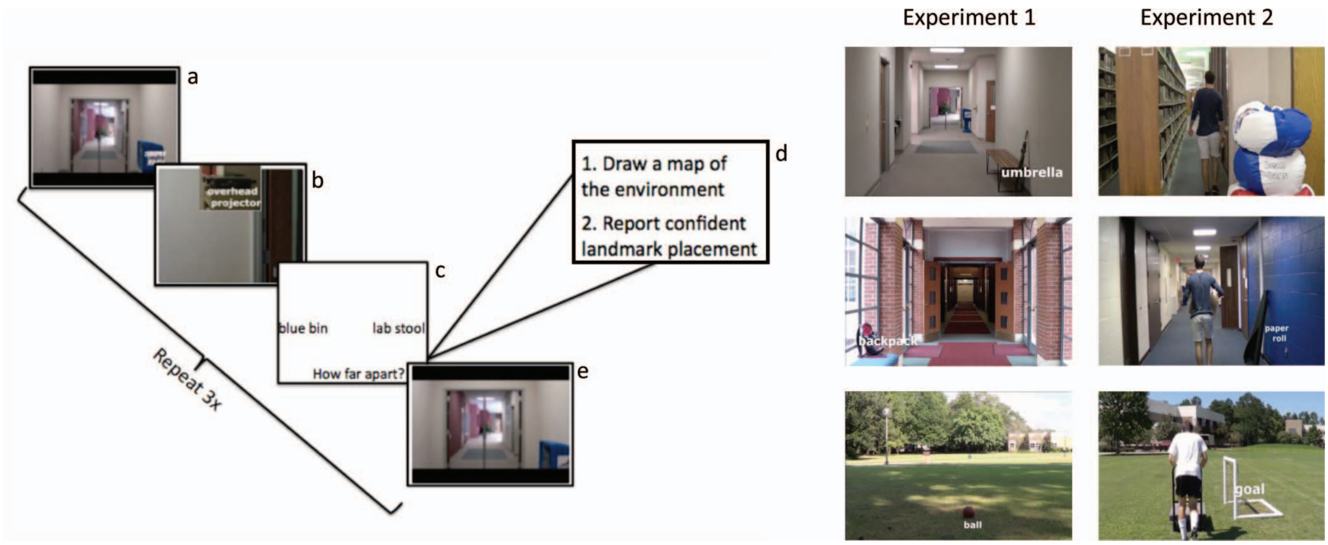

Figure 1. Stimuli and tasks in Experiments 1 and 2. The left panel depicts the timeline and tasks tested within each route, including (a) route viewing, (b) pointing task, (c) distance estimation task, (d) map drawing, and (e) segmentation of route. The right panel depicts still images of each of the environments in Experiment 1 and Experiment 2, respectively. See the online article for the color version of this figure.

ipants were given a list of the landmarks to ensure that all landmarks were placed on the map; landmarks were listed in either alphabetical or reverse alphabetical order. Figure 3 gives an example of a well-formed map and a poorly formed map. Maps were scored using the Gardony Map Drawing Analyzer tool (Gardony, Taylor, & Brunyé, 2016). From the Gardony Map Drawing Analyzer, the outcome of interest was distance accuracy, which measures the accuracy of scaling of interlandmark distances on the sketch maps produced by the subjects in reference to the correct map and produces a score ranging from 0–1 with higher values indicating better distance accuracy. (See Gardony et al., 2016 for full explanation of other available metrics).

After placing their landmarks, participants were then given a sheet of paper and asked to list those landmarks they were sure that they had placed correctly on their maps and to omit landmarks for which they were unsure of the location. Here we report only analysis of the full maps; see Supplemental Methods and Results for analysis and discussion of the analysis comparing full and partial map scores.

Spatial segmentation. Participants then viewed the video of the route once more and were asked to press the spacebar whenever they thought that one natural and meaningful unit of space ended, and another began. They were told there were no right or wrong ways to do this task. For each participant, we calculated their *segmentation agreement* score, or the extent to which an individual participant's pattern of button presses corresponds to that of the group (Kurby & Zacks, 2011; Zacks et al., 2006). This metric was calculated in a similar manner as has been described in previous studies and will be described only briefly here (Kurby & Zacks, 2011; Zacks et al., 2006). Each movie was divided into 1-s bins, and the proportion of participants that identified a boundary within each bin was calculated. Each individual's segmentation was also broken up into 1-s bins and coded as a "1" if a boundary was identified within that bin and a zero otherwise. Last, we calculated the correlation between each participants' segmentation and the overall group norm, scaling for the highest and lowest possible segmentation scores given the number of boundaries identified by each participant. Therefore, agreement scores ranged from 0 to 1 with higher scored indicating greater agreement with the group.

Nonspatial cognitive measures. Participants also completed a battery of tasks tapping working memory, verbal episodic memory and processing speed in a separate behavioral session. Specifically, our working memory construct included performance on Operation Span and Symmetry Span (Conway et al., 2005; Turner & Engle, 1989). Briefly, these are both complex span tasks involving a processing component and a storage component. For Symmetry Span, the processing task involves making symmetry decisions and the storage component involves remembering a highlighted location on a grid. In Operation Span, the processing task involves solving simple math problems and the storage component entails remembering a letter. In both tasks, processing and storage components are interleaved until participants are prompted to begin the recall phase by clicking on locations (Symmetry Span) or recalling letters (Operation Span) in the order they were presented. The verbal memory construct involved studying three different word lists comprising 30 words each for 2 min, and immediately recalling as many words as possible in a 5-min period (Small, Dixon, Hultsch, & Hertzog, 1999). Within each of these lists there were six sematic clusters comprising five items each; semantic clustering of recalled items was not considered in this study. The processing speed tasks included Letter Comparison (Salthouse & Babcock, 1991), Pattern Comparison (Salthouse & Babcock, 1991), and Finding As (Ekstrom, French, & Harman, 1979). Letter Comparison involved comparing two letter strings to indicate whether they were the same or different; participants were instructed to complete as many comparisons as possible in 20 seconds. Pattern Comparison mirrored the letter comparison task

Figure 2. Depiction of right-handed turn in the pointing task. The probed item stays on the screen until a response has been input by pressing {ENTER}. Each left/right button press advances the background view in increments of 5°. See the online article for the color version of this figure.

except here participants were comparing simple line patterns rather than letter strings. The Finding As task involved searching through a list of words and striking through any words containing the letter 'a' again, participants were told to strike through as many words containing the letter 'a' as possible in 30 seconds (see also Table 1). Tasks were given in a fixed order; tasks tapping the same cognitive construct were not given back-to-back. Older adult participants also completed the Short Blessed Test (Katzman et al., 1983) and Mini Mental State Exam (Folstein, Folstein, & McHugh, 1975) to ensure that they were cognitively normal. These tests were given at the end of the battery.

Procedure. Participants attended two sessions, the first lasting about 1 hr and 45 min and the second lasting about 1 hr and 15 min. The first session consisted of route viewing, the spatial memory tasks described above (pointing task, distance estimation task and map drawing) and the spatial segmentation task for all three routes. Participants completed all tasks for each route before moving onto the next route (see Figure 1 for a schematic of tasks and stimuli used in the first session). The second session consisted of the working memory, verbal episodic memory, and processing speed tasks, henceforth referred to as the cognitive battery. Upon completion of the second session, participants were debriefed as to the purpose of the study and the hypotheses being tested and were given the opportunity to ask questions.

Results

Statistical modeling was done using the lme4 (Bates, Mächler, Bolker, & Walker, 2015) and lmerTest (Kuznetsova, Brockhoff, & Christensen, 2014) packages in R (R Development Core Team, 2008), using the Satterthwaite approximation for degrees of freedom.

Age differences in spatial memory. To test for age differences in spatial memory performance, we fit linear mixed models (LMMs) for each task, treating subjects and routes as random effects and gender[2] and age as a fixed effect (modeled as a continuous variable). Pointing performance was coded as error scores, so lower values indicate better performance. As expected, old age was associated with significantly poorer performance in the pointing, $F(1, 73) = 52.09$, $p < .001$, distance estimation, $F(1, 73.14) = 18.89$, $p < .001$, and map drawing, $F(1, 73.12) = 36.06$, $p < .001$, tasks (see Table 2 for mean, *SD*, skew and kurtosis measures for each of the spatial tasks by Experiment and age group).

Interaction of age and spatial task type on performance. To compare the magnitude of age differences in performance across spatial measures, we z-scored the spatial measures and included them in a linear mixed model predicting spatial z score from fixed effects of gender, age, and task (with an interaction between age and task) and random effects of subject and route. In this model, we found a significant age × task interaction, $F(2, 526.03) = 4.18$, $p = .016$. Follow-up comparisons using the glht function in the multcomp package (Hothorn, Bretz, & Westfall, 2008) revealed that the magnitude of the main effect of age on z-scored pointing error and map drawing z scores did not differ

[2] Although we collected information about gender and balanced our sample for gender, as gender differences have been observed in spatial memory tasks (e.g., Postma, Jager, Kessels, Koppeschaar, & van Honk, 2004), we did not power our study to look for gender differences. We report only tests for which gender was a significant predictor in the text; full statistical information, means, and standard deviations by gender and age for both experiments can be found in the online supplemental materials (Supplemental Tables 1 and 2).

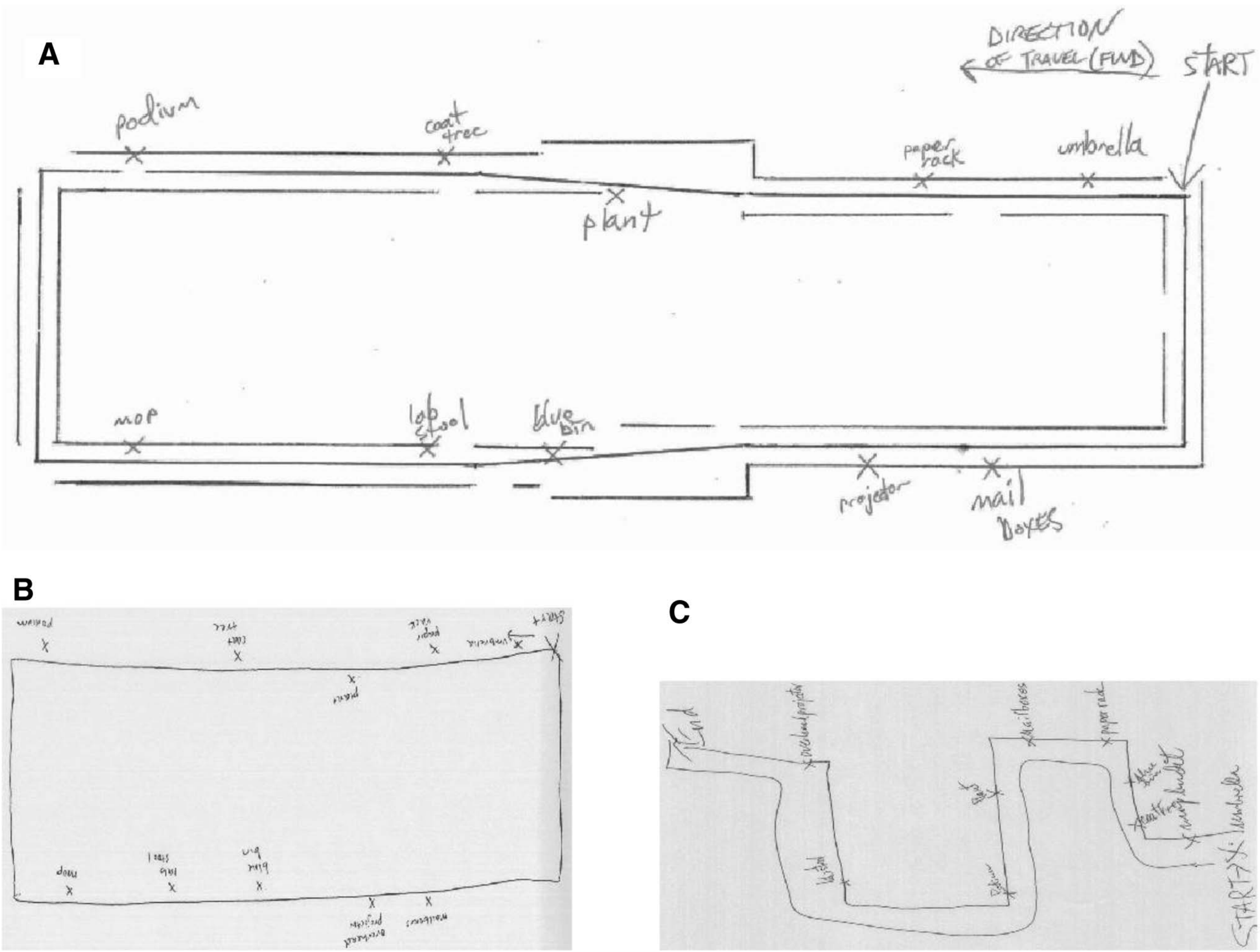

Figure 3. Examples of map drawings. Panel A depicts the correct map, panel B displays an example of a well-formed map, and panel C shows a poorly formed map.

from one another, $t(526) = 1.91$, $p = .138$, the magnitude of the main effect of age on *z*-scored pointing error was significantly larger than the magnitude of the effect of age on distance estimation z-scores, $t(526) = 2.89$, $p = .011$, and there was no significant difference between the main effect of age on *z*-scored map drawing performance and *z*-scored distance estimation, $t(526) = 1.10$, $p = .514$. In the linear mixed model described above, we also observed a main effect of age, $F(1, 74.56) = 61.46$, $p < .001$, and a main effect of task, $F(2, 526.58) = 3.30$, $p = .037$. Thus, advancing age was associated with a deleterious effect on performance for all of our spatial measures, but differentially so only in that age predicted performance more for the pointing task than for the distance estimation.

Age, nonspatial cognitive factors, and spatial memory measures. To explore the relationship between the nonspatial cognitive measures and spatial memory, we *z*-scored these measures and combined them to create separate nonspatial cognitive composite variables for working memory, processing speed and verbal memory. Each of the three spatial outcome measures (pointing, distance estimation, map drawing) were predicted in separate models. Model 1 included fixed effects of the cognitive composite variables (working memory, processing speed and verbal memory) and gender, and random effects of subject and route. Model 2 added a fixed effect of age (as a continuous variable) to those predictors specified in Model 1. Model 3 added interaction terms between age and the cognitive composites.[3] Models were then compared with one another using the 'anova' command in the lmerTest package for R (Kuznetsova et al., 2014) to determine the model that best fit the data. Here, our central question was whether age adds any explanatory power to our model after accounting for nonspatial cognitive functioning (Model 2 vs. Model 1). Model 3

[3] Because Symmetry Span involves spatial working memory, we re-ran each of the linear mixed model comparisons reported in this paper using a *z* score for only Operation Span rather than the combined working memory *z* score and obtained similar results to those reported in the main text. In some cases, we found support for more complex models providing best fit, which is in the opposite direction predicted by the concern that our results were driven by the similarity between the spatial WM task and our experimental spatial measures.

Table 1
Nonspatial Tasks

Construct	Measure	Description
Processing speed	Finding as	Strike through as many words containing the letter 'a' in 2 minutes
	Letter comparison	20 s to determine whether strings of letters are the same or different
	Pattern comparison	20 s to determine whether line patterns are the same or difference
Working memory	Operation span	Remember sequences of letters while solving math problems
	Symmetry span	Remember location of colored squares while making symmetry judgments
Verbal memory	Word list recall	Study a list of 30 words (5 semantic clusters, 6 items in each) for 2 minutes; recall as many words as possible in 5 minutes. Three different lists were presented.

was built to assess whether the form of the relationship between spatial memory and nonspatial cognitive measures differed as a function of age.

Pointing task. For the pointing task, Model 3 best fit the data, $\chi^2(3) = 12.81$, $p = .005$ (see Table 4 for correlations among composite nonspatial measures, nonspatial composites and age, and standardized Cronbach's alphas for each nonspatial composite).[4] To investigate the nature of the interactions between the cognitive measures and age, pointing error was averaged across the two routes that contained the pointing task for each subject and then these average scores were correlated with each cognitive composite, separately for younger and older adults. The nonspatial cognitive variables significantly predicted performance for the older adult group but not for the younger adults. (See Table 3 for correlations between spatial and nonspatial cognitive measures, as well as Supplemental Figure 1 and Experiment 1 Supplemental Results for additional mediation analysis.)

Distance estimation task. Turning to the estimates of distance between pairs of landmarks, Models 2 and 3 did not produce a better fit than Model 1 [fixed effect of gender and nonspatial cognitive composites; Model 2 compared with Model 1: $\chi^2(1) = 1.48$, $p = .225$ and Model 3 compared with Model 1: $\chi^2(4) = 3.83$, $p = .429$]. The cognitive variables were related to the ability to accurately estimate distances between objects for all participants (see Supplemental Figure 1 and Table 3).

Map drawing task. With respect to the map drawing scores, Models 2 and 3 did not produce a better fit than Model 1 [fixed effect of gender and cognitive composites; comparing fit for Model 2 compared with Model 1: $\chi^2(1) = 2.82$, $p = .093$ and Model 3 to Model 1: $\chi^2(4) = 6.37$, $p = .173$]. The cognitive variables were related to map drawing ability across the life span (see Supplemental Figure 1 and Table 3). With respect to processing speed, we should note that our older adult sample mainly clustered toward the lower end of our *z*-score range, whereas younger adults were more likely to exhibit high *z*-scores. This is consistent with many other studies showing slowing in older adulthood (Salthouse, 1996). Cognitive abilities predicted performance for both our younger and older adult samples on the map drawing task, which requires the creation of environment-centered spatial representations from exposure to a route from the egocentric perspective. This suggests that nonspatial abilities influence egocentric-to-environment-centered transformations similarly younger and older adults.

Age, segmentation agreement, and spatial memory measures. To evaluate whether segmentation agreement predicted spatial memory performance, we used an approach similar to that for the nonspatial cognitive measures: We fit a reduced Model 1 that predicted each measure from only fixed effects of gender and segmentation agreement and random effects of subject and route, and a Model 2 that added a fixed effect of age.

For all three measures, Model 2 provided a better fit [pointing error: $\chi^2(1) = 37.27$, $p < .001$; distance estimation: $\chi^2(1) = 14.73$, $p < .001$; map drawing: $\chi^2(1) = 25.11$, $p < .001$]. Segmentation agreement was not a significant predictor of any of the measures [pointing error: $F(1, 138.270) = 0.40$, $p = .531$; distance estimation: $F(1, 214.81) = 0.14$, $p = .713$; map drawing: $F(1, 214.21) = 0.27$, $p = .606$].

Relationships between segmentation agreement and the other nonspatial measures. To fully characterize the relationship between our spatial segmentation and nonspatial measures, we conducted bivariate correlations across subjects between segmentation agreement and each of the cognitive composite variables. We saw significant correlations between each of the nonspatial measures and segmentation agreement scores (see Table 3). Segmentation agreement scores were also negatively correlated with age, $r(73) = -0.50$, $p < .001$.

Discussion

In this first experiment, we replicated previous findings that older adults have more difficulty with spatial navigation and spatial memory tasks than younger adults (e.g., Head & Isom, 2010). We extended this prior work by comparing the effect of age and task in predicting performance on multiple indicators of spatial memory, and by relating performance on the spatial memory measures to performance in nonspatial cognitive domains. Although older adults exhibited poorer performance on all spatial measures compared with younger adults, they were differentially impaired on the pointing task in comparison with the distance estimation task. The pointing task involved directly indicating self-to-object directions. Given that older adults seem to prefer the egocentric reference frame (Moffat & Resnick, 2002), this was a somewhat unexpected result. However, assuming that long-term spatial memory is likely stored in an environment-centered reference frame (e.g., Burgess,

[4] To address the possibility that this result stems from larger variability in the older adult data compared with the younger adult data, we conducted a parallel analysis in which we *z*-scored pointing error performance separately for each group, so that the means and *SD*s of each groups' pointing performance were equated with one another. The results were similar to those reported in the main text; again, Model 3 gave the best fit, $\chi^2(3) = 8.78$, $p = .032$.

Table 2
Mean (Standard Deviation), Skew, and Kurtosis for Spatial Measures Separated by Experiment and Age Group

Measure	Experiment 1		Experiment 2	
	Younger adults	Older adults	Younger adults	Older adults
Raw scores				
Pointing error	20.61 (9.35)	42.66 (18.03)	27.07 (11.59)	47.73 (19.25)
	1.71, **3.82**	*0.20*, **−0.75**	*1.64*, **3.14**	*0.33*, **−1.25**
Scaled distance estimation	0.90 (0.38)	0.59 (0.28)	0.93 (0.36)	0.59 (0.34)
	−0.62, **−0.50**	*0.66*, **−0.31**	*−0.02*, **1.03**	*0.38*, **−0.43**
Map drawing (distance accuracy)	0.85 (0.04)	0.79 (0.04)	0.85 (0.03)	0.82 (0.05)
	0.28, **−1.07**	*−0.05*, **−1.13**	*−0.14*, **−0.50**	*−0.07*, **0.98**
z scores				
Pointing error (reverse scored)	0.55 (0.58)	−0.55 (1.04)	0.47 (0.66)	−0.47 (1.06)
Scaled distance estimation	0.33 (1.05)	−0.33 (0.83)	0.34 (0.96)	−0.35 (0.92)
Map drawing (distance accuracy)	0.41 (0.88)	−0.42 (0.95)	0.25 (0.86)	−0.25 (1.07)

Note. Each participant contributed one value in each cell (i.e. spatial memory measures were averaged over all three routes for each subject first before taking the group mean). Skew and Kurtosis not provided for *z* scores. Skew values are italicized, and kurtosis values are given in bold.

Becker, King, & O'Keefe, 2001), the pointing task also seems to involve the greatest number of translations between frames of reference, from egocentric at encoding, into environment centered in long term memory, and back into egocentric at retrieval. So, this finding might be in line with our prediction that tasks requiring translation and coordination across multiple frames of reference are more difficult for older compared with younger adults.

Further, we found that, for older adults, performance on the nonspatial cognitive measures (working memory, processing speed and verbal memory) predicted how well they perform in the pointing task. These variables did not predict pointing performance for younger adults, but the data suggest that ceiling effects (i.e., pointing error scores closer to 0°) may have limited our ability to detect effects in this group. These results provide initial evidence that the direct relationship between advancing age and pointing error is reduced after accounting for performance on nonspatial cognitive measures and may suggest a role for cognitive reserve in conferring a protective effect against the typical pattern of age-related degradation in spatial memory. Perhaps more importantly, this analysis suggests that the role of nonspatial cognitive abilities should be considered when investigating the relationship between age and spatial memory. Last, we found that performance on our nonspatial variables predicted performance on the map drawing and distance estimation tasks for all participants, and that adding age to the model did not significantly improve the model fit.

Across the board, we found that spatial segmentation ability did not predict spatial memory performance. This is a surprising finding given the wealth of prior literature relating event segmentation agreement and event memory (e.g., Sargent et al., 2013). To more directly test whether the relationship between segmentation agreement and event memory observed in materials depicting everyday events (e.g., Sargent et al., 2013) extends to spatial memory, we designed materials that depicted an actor performing a goal-directed activity as he navigated through an environment. Using these materials, we asked participants to engage in event segmentation, rather than spatial segmentation, to make the segmentation measure more directly comparable to prior studies (Kurby & Zacks, 2011; Zacks et al., 2006).

Table 3
Correlation Matrix for Spatial and Nonspatial Cognitive Measures

Measure	Experiment 1			Experiment 2		
	Working memory	Processing speed	Verbal memory	Working memory	Processing speed	Verbal memory
Pointing error						
Older adults	$-.42^{**}$	$-.45^{**}$	$-.45^{**}$	$-.51^{**}$	$-.33^{*}$	.07
Younger adults	−.02	.19	−.01	$-.42^{*}$	−.03	.15
Scaled distance estimation	$.51^{***}$	$.26^{*}$	$.45^{***}$	$.55^{***}$	$.47^{***}$	$.36^{**}$
Map drawing (distance accuracy)	$.56^{***}$	$.41^{***}$	$.56^{***}$	$.50^{***}$	$.43^{***}$	$.25^{*}$
Segmentation agreement	$.30^{**}$	$.32^{**}$	$.31^{**}$	$.25^{*}$	.18	.04

Note. Separate correlations provided for older and younger adult samples for pointing error, as support was found for the model containing an interaction between age and cognitive performance in predicting pointing error in Experiment 1. Processing speed *z* score was missing for one younger adult participant in Experiment 1. All other reported correlations represent data for the full sample.
$^{*} p < .05$. $^{**} p < .01$. $^{***} p < .001$.

Table 4
Cronbach's Alphas for Composite Measures and Correlations Between Composites and Age Across Both Experiments

Measure	Working memory composite	Processing speed composite	Verbal memory composite
Age	−.67	−.67	−.63
Working memory composite	.77	.61	.55
Processing speed composite		.79	.65
Verbal memory composite			.89

Note. Standardized Cronbach's alphas displayed on diagonal. Cronbach's alphas computed using "alpha" function in psych package for *R* (Revelle, 2018).

Experiment 2

Method

Participants. Participants were 36 younger adults (50% female, median: 20.0, range: 18–23 years) and 36 older adults (50% female, median: 72.0, range: 66–79 years, median years of education: 16.0, range: 12–21 years; years of education missing for 11 participants). Younger adult participants were recruited through the psychology department subject pool, and older adults were recruited from the St. Louis community using the Department of Psychological & Brain Sciences Older Adult participant pool and Volunteer for Health participant pool. Younger adults were compensated with either $10 per hour or one credit per hour of participation; older adults received $10 an hour for participation.

Materials. Participants watched videos of an actor navigating around an environment in each of three different routes. In each video, the actor performed a series of goal-directed activities as he navigated the environment, such as reshelving returned books and pulling requested books in a library and setting up drills and stations for soccer practice (see Figure 1). At the start of each video, participants saw a short vignette that set up the goal-directed activity that the actor would be performing before the actor started to navigate along the route, with a cameraperson following approximately 2 m behind. As in Experiment 1, participants were told to pay attention to the landmarks because they were going to be asked to remember the placement of the landmarks later. There were two alternate versions of each route. The landmarks were in the same locations in both versions, but the event boundaries occurred at different locations to test hypotheses about chunking which are addressed elsewhere (see Footnote 1). Participants saw only one version of each video, with alternate versions counterbalanced across participants. All other tasks and materials were as described for Experiment 1.

Procedure. The procedure for both sessions proceeded as described in Experiment 1, with the exception that for the route segmentation task, participants in Experiment 2 were instructed to engage in event segmentation (Kurby & Zacks, 2011; Zacks et al., 2006) rather than spatial segmentation. Participants were instructed to press the spacebar during the videos whenever they believed that one natural and meaningful unit of activity began and another ended. For the event segmentation task, one subject failed to provide segmentation for one route and one additional subject failed to provide segmentation for two of the three routes.

Results

Statistical modeling was performed in the same way as in Experiment 1.

Age differences in spatial memory. Age differences and map drawing analyses were conducted in the same fashion as described in Experiment 1. The results of Experiment 2 were largely consistent with Experiment 1. Age was associated with poorer performance on the pointing task, $F(1, 69) = 33.33$, $p < .001$, the distance estimation task,[5] $F(1, 69.24) = 19.01$, $p < .001$, and the map drawing task, $F(1, 69) = 10.59$, $p = .002$ (see Table 2 for descriptive statistics). Gender was a significant predictor for pointing, $F(1, 69) = 4.31$, $p = .042$, and map drawing, $F(1, 69) = 6.37$, $p = .014$, with males outperforming females in both cases.

Interaction of age and spatial task type on performance. To compare the magnitude of age differences in performance across spatial measures, we utilized the analysis scheme described above in Experiment 1. Here, we again observe a significant age × task interaction, $F(2, 497.09) = 3.07$, $p = .047$. Follow-up comparisons using the glht function from the multcomp package (Hothorn et al., 2008) revealed that the magnitude of the main effect of age on *z*-scored pointing error was significantly larger than the magnitude of the effect of age on the map drawing *z* scores, $t(497) = 2.48$, $p = .036$, there was no significant difference between the magnitude of the main effect of age on *z*-scored pointing performance and *z*-scored distance estimation, $t(497) = 1.41$, $p = .337$, and no significant difference between the magnitude of the main effect of age on z-scored map drawing performance and *z*-scored distance estimation scores, $t(497) = -1.19$, $p = .457$. As in Experiment 1, we found main effects of age, $F(1, 70.81) = 38.12$, $p < .001$, and task, $F(2, 498.88) = 10.45$, $p < .001$. Again, advancing age exerted a deleterious effect on performance on all spatial measures, but only significantly so for the pointing task.

Age, nonspatial cognitive factors and spatial memory measures. As before, linear mixed models were compared with one another, where Model 1 contained only fixed effects of the *z*-scored nonspatial cognitive measures and gender and random effects of subject and route. Model 2 added a fixed effect of age to the predictors specified in Model 1, and Model 3 allowed for interactions between age and nonspatial cognitive measures.

Pointing task. In contrast to the finding from Experiment 1, Model 2 gave a marginally better fit than Model 1, $\chi^2(1) = 3.43$, $p = .064$. Cognitive variables were related to performance on the spatial tasks, but in this case not differentially so for younger and older adults (see Table 4 for correlation matrix and Cronbach's alphas, and Experiment 2 Supplemental Results and Supplemental Figure 2 for mediation analysis and visual depiction of these data).

To test whether the relationship between age and pointing error differed across experiments, we built a LMM predicting pointing error as a function of age and experiment (with an age × experiment interaction) and with subject and route coded as random effects. Although pointing error was numerically higher in Experiment 2 ($M = 37.4$, $SD = 21.88$) compared with Experiment 1 ($M = 31.63$, $SD = 20.28$), we found no significant differences in

[5] Distance estimation data were missing for one route for one participant.

pointing error across experiments, $F(1, 144) = 2.43$, $p = .122$, nor an age × experiment interaction, $F(1, 144) = 0.17$, $p = .676$, suggesting that the two experiments did not differ substantially from one another in terms of the magnitude of pointing errors produced or the effect of age on those errors. As expected, there was a significant main effect of age, $F(1, 144) = 79.59$, $p < .001$.

Distance estimation task. As in Experiment 1, Models 2 and 3 did not produce a better fit than Model 1 [fixed effect of gender and nonspatial cognitive variables; Model 2 compared with Model 1: $\chi^2(1) = 0.07$, $p = .789$ and Model 3 compared with Model 1: $\chi^2(4) = 0.77$, $p = .943$]. Performance on the nonspatial cognitive tasks was related to the ability to estimate distances between pairs of objects (see Supplemental Figure 2 and Table 3).

Map drawing task. Consistent with Experiment 1, Model 1 produced the best fit, including fixed effects of gender and nonspatial cognitive variables [comparing fit for Model 2 compared with Model 1: $\chi^2(1) = 0.01$, $p = .919$ and Model 3 to Model 1: $\chi^2(4) = 0.63$, $p = .960$]. Performance in the nonspatial cognitive domains was related to successful completion of the map drawing task (see Supplemental Figure 2 and Table 3), supporting the idea that after nonspatial cognitive functioning has been taken into account, older and younger adults perform similarly on this task.

Age, segmentation agreement, and spatial memory measures. Replicating the findings of the spatial segmentation task in Experiment 1, Model 2 (predicting pointing error with fixed effects of gender, age and event segmentation scores) produced best fit for pointing error, $\chi^2(1) = 27.18$, $p < .001$, distance estimation ability, $\chi^2(1) = 17.08$, $p < .001$, and map drawing, $\chi^2(1) = 10.38$, $p = .001$, but segmentation agreement scores were not a significant predictor of performance on the spatial measures [pointing error: $F(1, 116.65) = 0.66$, $p = .420$; distance estimation: $F(1, 214.81) = 0.14$, $p = .713$ and map drawing: $F(1, 170.48) = 1.37$, $p = .244$].

Relationships between segmentation agreement and the other nonspatial measures. Working memory was related to segmentation agreement, whereas neither processing speed nor verbal memory were correlated with segmentation agreement scores in this experiment (see Table 3). In addition, the negative correlation between age and segmentation agreement scores observed in Experiment 1 was not significant in this sample, $r(70) = -0.11$, $p = .374$.

Discussion

The findings of Experiment 2 largely replicated the patterns observed in Experiment 1, with some important exceptions. We found support for age-related degradation in spatial memory performance, replicating both Experiment 1 and other prior work (e.g., Head & Isom, 2010). Regarding the effect of age on pointing performance, we found a stronger effect of age on pointing performance in comparison to map drawing. Unlike in Experiment 1, we did not find a difference in the effect of age on pointing performance compared with distance estimation ability. We again found that all experimental spatial measures (pointing error, distance estimation and map drawing) were related to performance on nonspatial cognitive measures.

In contrast to Experiment 1, here we did not observe interactions between age and nonspatial variables predicting pointing error. This supports the possibility that the interaction observed in Experiment 1 was at least partially driven by a skewed distribution and a ceiling effect in pointing performance for younger adults, which made it impossible to detect effects of nonspatial variables on pointing in that group. We did find that working memory predicted pointing performance in both younger and older adults; further, we found a correlation between processing speed and pointing error that reached significance for older adults, but not for our younger adult sample. We also replicated the null findings from Experiment 1 regarding the lack of a relationship between segmentation agreement and spatial memory.

General Discussion

Across two experiments, we found that older adults' spatial memory was poorer than younger adults'. Age-related deficits were greatest in pointing task. This task relied most on an egocentric frame of reference, and likely involved the greatest number of transformations between reference frames. In both experiments, map drawing performance and distance estimation ability was associated with nonspatial task performance for our entire sample, and models containing age did not significantly improve model fit. Thus, the form of the relationship between age and nonspatial cognitive variables differed depending on the specific spatial task being predicted. Moreover, the degree to which other cognitive faculties are implicated in successful spatial memory performance may differ for older and younger adults. However, results were not consistent on this issue across experiments and thus are interpreted with caution. Finally, across two experiments we found little evidence that segmentation ability contributed to spatial memory performance.

Selective Impairment of Pointing

It is interesting that older adults tend to prefer egocentric navigation strategies (e.g., Moffat & Resnick, 2002), but in the current study the task that depended most heavily on one's egocentric perspective—pointing—was the only one that showed age-related decline after accounting for general cognitive abilities. Further, we found evidence in both experiments that pointing performance was specifically impaired in older adults in comparison to the other two spatial memory tasks (distance estimation in Experiment 1 and map drawing in Experiment 2). The pointing task depends more heavily on the *transformation* of the egocentric reference frame relative to the environment-centered reference frame, whereas distance estimation and map drawing likely depend mostly on *access* to information in an environment-centered reference frame. One speculative possibility is that aging selectively affects reference frame transformation, whereas age-related differences in reference frame access are accounted for by general cognitive differences.

Toward Situating Spatial Navigation Within a Broader Context

In considering spatial memory within the broader context of the nonspatial cognitive ability measures, it is noteworthy that, in this dataset, we find no evidence of age-related degradation in distance estimation or map drawing ability once nonspatial cognitive functioning is taken into account. While map drawing has been a widely used task to tap spatial memory, many of these studies do not measure nonspatial cognitive functioning; as a result, deficits in map drawing are often attributed to age (Iaria et al., 2009). The current data suggest that much of the degradation in map drawing and distance estimation ability observed in older adults may be attributed to more generalized cognitive decline associated with age. It would be valuable to follow up these patterns in larger samples, but it is worth noting that our conclusions would be quite different were we not to consider the nonspatial cognitive measures. Omitting consideration of the nonspatial measures, we observe a general age-related impairment on all three of the spatial measures, consistent with many previous studies—only when cognitive performance in other domains is considered do we see a more selective pattern of age differences. This highlights the value of looking at spatial age differences in a broader context.

Segmentation Ability and Spatial Memory

Across two experiments, we consistently found that segmentation agreement did not significantly predict any of the spatial memory measures. This was a surprising finding, given the strong relation between segmentation agreement scores and event memory that has been demonstrated across the life span in prior research (Flores et al., 2017; Kurby & Zacks, 2011; Sargent et al., 2013; Zacks et al., 2006). However, there are some important differences between previous studies and the current work that may serve as the basis for these differential findings. Perhaps most important, these environments were not familiar to our participants, whereas the everyday activities used in previous studies were generally familiar household tasks. It is possible that, while learning a novel environment (and possibly observing novel activities), the ability to identify normative breakpoints in a continuous stream of activity confers less advantage than in everyday-type tasks. A second possibility is that segmenting information in a normative fashion is important for the organization of 'what' type information (e.g., steps within a sequence of activity, narrative description of features of the location or what was happening in that location) but is less helpful for coding of 'where' information. To recall a sequence of actions it is likely of value to be able to construct a series of mental simulations of those actions, including visual information, internal thoughts, and other contextual cues present during encoding. Such mental event reconstruction may be less helpful for retrieving the location of objects whose location in the environment is fixed.

Conclusions

In two experiments, we found that older adults had more difficulty on tests of spatial memory than did younger adults, and that spatial memory performance was related to nonspatial cognitive ability. Our pointing task was more sensitive to age-related differences than the distance estimation or map drawing tasks. Practically speaking, this suggests that the pointing task is a measure worth emphasizing in future studies. Theoretically, this finding suggests that older adults' differential performance on different spatial tasks may have less to do with egocentric versus environment centered reference frames and more to do with the degree of transformation between the different frames. Also, the relationship between spatial and nonspatial abilities does not seem to be merely a matter of global cognitive ability. Instead, different aspects of spatial performance were predicted best by different nonspatial abilities, and in some cases these relationships differed across the life span. These data thus support a nuanced view of age-related differences in spatial ability, in which age differences in navigation strategy may play a key role. Thus, explaining age differences in spatial memory will benefit from incorporating age-related strategy differences and from taking advantage of robust memory measures. With respect to improving older adults' wayfinding skills, consideration of both spatially specific processes and other cognitive limitations present in older adult samples may lead to more useful intervention strategies than those that focus on spatial memory or navigational processes alone.

References

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*. http://dx.doi.org/10.18637/jss.v067.i01

Burgess, N., Becker, S., King, J. A., & O'Keefe, J. (2001). Memory for events and their spatial context: Models and experiments. *Philosophical Transactions of the Royal Society of London Series B: Biological Sciences, 356,* 1493–1503. http://dx.doi.org/10.1098/rstb.2001.0948

Burns, P. C. (1999). Navigation and the mobility of older drivers. *The Journals of Gerontology: Series B: Psychological Sciences and Social Sciences, 54,* S49–S55. http://dx.doi.org/10.1093/geronb/54B.1.S49

Colombo, D., Serino, S., Tuena, C., Pedroli, E., Dakanalis, A., Cipresso, P., & Riva, G. (2017). Egocentric and allocentric spatial reference frames in aging: A systematic review. *Neuroscience and Biobehavioral Reviews, 80,* 605–621. http://dx.doi.org/10.1016/j.neubiorev.2017.07.012

Conway, A. R., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin & Review, 12,* 769–786. http://dx.doi.org/10.3758/BF03196772

Ekstrom, R. B., French, J. W., & Harman, H. H. (1979). Cognitive factors: Their identification and replication. *Multivariate Behavioral Research Monographs, 79,* 84.

Filimon, F. (2015). Are all spatial reference frames egocentric? Reinterpreting evidence for allocentric, object-centered, or world-centered reference frames. *Frontiers in Human Neuroscience, 9,* 648. http://dx.doi.org/10.3389/fnhum.2015.00648

Flores, S., Bailey, H. R., Eisenberg, M. L., & Zacks, J. M. (2017). Event segmentation improves event memory up to one month later. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 43,* 1183–1202. http://dx.doi.org/10.1037/xlm0000367

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state": A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research, 12,* 189–198. http://dx.doi.org/10.1016/0022-3956(75)90026-6

Gardony, A. L., Taylor, H. A., & Brunyé, T. T. (2016). Gardony Map Drawing Analyzer: Software for quantitative analysis of sketch maps. *Behavior Research Methods, 48,* 151–177. http://dx.doi.org/10.3758/s13428-014-0556-x

Gold, D. A. (2012). An examination of instrumental activities of daily living assessment in older adults and mild cognitive impairment. *Journal of Clinical and Experimental Neuropsychology, 34,* 11–34. http://dx.doi.org/10.1080/13803395.2011.614598

Harris, M. A., Wiener, J. M., & Wolbers, T. (2012). Aging specifically impairs switching to an allocentric navigational strategy. *Frontiers in Aging Neuroscience, 4,* 29. http://dx.doi.org/10.3389/fnagi.2012.00029

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. In G. H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (pp.

193–225). San Diego, CA: Academic Press. http://dx.doi.org/10.1016/S0079-7421(08)60041-9

Head, D., & Isom, M. (2010). Age effects on wayfinding and route learning skills. *Behavioural Brain Research, 209,* 49–58. http://dx.doi.org/10.1016/j.bbr.2010.01.012

Hegarty, M., Montello, D. R., Richardson, A. E., Ishikawa, T., & Lovelace, K. (2006). Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning. *Intelligence, 34,* 151–176. http://dx.doi.org/10.1016/j.intell.2005.09.005

Hegarty, M., Richardson, A., Montello, D., Lovelace, K., & Subbiah, I. (2002). Development of a self-report measure of environmental spatial ability. *Intelligence, 30,* 425–447. http://dx.doi.org/10.1016/S0160-2896(02)00116-2

Hegarty, M., & Waller, D. (2005). Individual differences in spatial abilities. In A. Mikaye & P. Shah (Eds.), *The Cambridge handbook of visuospatial thinking* (pp. 121–169). Cambridge, UK: Cambridge University Press.

Horn, J. L., & Cattell, R. B. (1967). Age differences in fluid and crystallized intelligence. *Acta Psychologica, 26,* 107–129. http://dx.doi.org/10.1016/0001-6918(67)90011-X

Hothorn, T., Bretz, F., & Westfall, P. (2008). Simultaneous inference in general parametric models. *Biometrical Journal Biometrische Zeitschrift, 50,* 346–363. http://dx.doi.org/10.1002/bimj.200810425

Iaria, G., Palermo, L., Committeri, G., & Barton, J. J. S. (2009). Age differences in the formation and use of cognitive maps. *Behavioural Brain Research, 196,* 187–191. http://dx.doi.org/10.1016/j.bbr.2008.08.040

Katzman, R., Brown, T., Fuld, P., Peck, A., Schechter, R., & Schimmel, H. (1983). Validation of a short Orientation-Memory-Concentration Test of cognitive impairment. *The American Journal of Psychiatry, 140,* 734–739. http://dx.doi.org/10.1176/ajp.140.6.734

Khooshabeh, P., Hegarty, M., & Shipley, T. F. (2013). Individual differences in mental rotation: Piecemeal versus holistic processing. *Experimental Psychology, 60,* 164–171. http://dx.doi.org/10.1027/1618-3169/a000184

Klencklen, G., Després, O., & Dufour, A. (2012). What do we know about aging and spatial cognition? Reviews and perspectives. *Ageing Research Reviews, 11,* 123–135. http://dx.doi.org/10.1016/j.arr.2011.10.001

Kurby, C. A., & Zacks, J. M. (2011). Age differences in the perception of hierarchical structure in events. *Memory & Cognition, 39,* 75–91. http://dx.doi.org/10.3758/s13421-010-0027-2

Kuznetsova, A., Brockhoff, P., & Christensen, R. B. (2014). lmerTest: Tests in linear mixed effects models. http://CRAN.R-Project.Org/Package=LmerTest

Lawton, M. P., & Brody, E. M. (1969). Assessment of older people: Self-maintaining and instrumental activities of daily living. *The Gerontologist, 9,* 179–186. http://dx.doi.org/10.1093/geront/9.3_Part_1.179

Lemay, M., Bertram, C. P., & Stelmach, G. E. (2004). Pointing to an allocentric and egocentric remembered target in younger and older adults. *Experimental Aging Research, 30,* 391–406. http://dx.doi.org/10.1080/03610730490484443

Moffat, S. D. (2009). Aging and spatial navigation: What do we know and where do we go? *Neuropsychology Review, 19,* 478–489. http://dx.doi.org/10.1007/s11065-009-9120-3

Moffat, S. D., & Resnick, S. M. (2002). Effects of age on virtual environment place navigation and allocentric cognitive mapping. *Behavioral Neuroscience, 116,* 851–859. http://dx.doi.org/10.1037/0735-7044.116.5.851

Paxton, J. L., Barch, D. M., Storandt, M., & Braver, T. S. (2006). Effects of environmental support and strategy training on older adults' use of context. *Psychology and Aging, 21,* 499–509. http://dx.doi.org/10.1037/0882-7974.21.3.499

Postma, A., Jager, G., Kessels, R. P. C., Koppeschaar, H. P. F., & van Honk, J. (2004). Sex differences for selective forms of spatial memory. *Brain and Cognition, 54,* 24–34. http://dx.doi.org/10.1016/S0278-2626(03)00238-0

R Development Core Team. (2008). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.R-project.org

Revelle, W. (2018). *psych: Procedures for psychological, psychometric, and personality research*. Evanston, IL: Northwestern University. Retrieved from https://CRAN.R-project.org/package=psych

Rodgers, M. K., Sindone, J. A., III, & Moffat, S. D. (2012). Effects of age on navigation strategy. *Neurobiology of Aging, 33,* 202.e15–202.e22. http://dx.doi.org/10.1016/j.neurobiolaging.2010.07.021

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review, 103,* 403–428. http://dx.doi.org/10.1037/0033-295X.103.3.403

Salthouse, T. A., & Babcock, R. L. (1991). Decomposing adult age differences in working memory. *Developmental Psychology, 27,* 763–776. http://dx.doi.org/10.1037/0012-1649.27.5.763

Sargent, J. Q., Zacks, J. M., Hambrick, D. Z., Zacks, R. T., Kurby, C. A., Bailey, H. R., . . . Beck, T. M. (2013). Event segmentation ability uniquely predicts event memory. *Cognition, 129,* 241–255. http://dx.doi.org/10.1016/j.cognition.2013.07.002

Small, B. J., Dixon, R. A., Hultsch, D. F., & Hertzog, C. (1999). Longitudinal changes in quantitative and qualitative indicators of word and story recall in young-old and old-old adults. *The Journals of Gerontology: Series B: Psychological Sciences and Social Sciences, 54,* 107–115. http://dx.doi.org/10.1093/geronb/54B.2.P107

Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language, 28,* 127–154. http://dx.doi.org/10.1016/0749-596X(89)90040-5

Wang, R. F., & Brockmole, J. R. (2003a). Human navigation in nested environments. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29,* 398–404. http://dx.doi.org/10.1037/0278-7393.29.3.398

Wang, R. F., & Brockmole, J. R. (2003b). Simultaneous spatial updating in nested environments. *Psychonomic Bulletin & Review, 10,* 981–986. http://dx.doi.org/10.3758/BF03196562

Webber, L. S., & Hansen, L. R. (2000). Younger and older adults' use of street directories to plan travel. *Australian Journal of Psychology, 52,* 29–33. http://dx.doi.org/10.1080/00049530008255364

Weisberg, S. M., Schinazi, V. R., Newcombe, N. S., Shipley, T. F., & Epstein, R. A. (2014). Variations in cognitive maps: Understanding individual differences in navigation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40,* 669–682. http://dx.doi.org/10.1037/a0035261

Zacks, J. M., & Michelon, P. (2005). Transformations of visuospatial images. *Behavioral and Cognitive Neuroscience Reviews, 4,* 96–118. http://dx.doi.org/10.1177/1534582305281085

Zacks, J. M., Speer, N. K., Vettel, J. M., & Jacoby, L. L. (2006). Event understanding and memory in healthy aging and dementia of the Alzheimer type. *Psychology and Aging, 21,* 466–482. http://dx.doi.org/10.1037/0882-7974.21.3.466

Zacks, J. M., Tversky, B., & Iyer, G. (2001). Perceiving, remembering, and communicating structure in events. *Journal of Experimental Psychology: General, 130,* 29–58. http://dx.doi.org/10.1037/0096-3445.130.1.29

Received July 7, 2017
Revision received June 15, 2018
Accepted June 23, 2018 ■