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Event memory uniquely predicts memory for large-scale space

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Abstract

When a person explores a new environment, they begin to construct a spatial representation of it. Doing so is important for navigating and remaining oriented. How does one's ability to learn a new environment relate to one's ability to remember experiences in that environment? Here, 208 adults experienced a first-person videotaped route, and then completed a spatial map construction task. They also took tests of general cognitive abilities (working memory, laboratory episodic memory, processing speed, general knowledge) and of memory for familiar, everyday activities (event memory). Regression analyses revealed that event memory (memory for everyday events and their temporal structure), laboratory episodic memory (memory for words and pictures) and gender were unique predictors of spatial memory. These results implicate the processing of temporal structure and organization as an important cognitive ability in large-scale spatial-memory-from-route experience. Accounting for the temporal structure of people's experience while learning the layout of novel spaces may improve interventions for addressing navigation problems.

Keywords Spatial cognition · Memory · Individual differences

Humans moving through larger environments are typically exposed to a sequence of vistas containing objects and landmarks. The ability to remember landmark locations is useful for everyday navigation. In environments that are too large or cluttered to be seen from a single viewpoint, interlandmark spatial relationships must be encoded based on piecemeal route perspective views. Thus, one of the distinguishing features of spatial knowledge acquired from route experience is that it involves the integration of incoming perceptual information over time into organized, evolving knowledge structures (Ittelson, 1973; Wolbers & Hegarty, 2010). The temporal organization of extended experience is also important for understanding and remembering other, nonspatial aspects of everyday activities and events in general (e.g., Radvansky & Zacks, 2014; Rubin & Umanath, 2015). In the current study, we test the hypothesis that memory for where things are, based on viewing temporally extended route experiences, will be uniquely predicted by the ability to remember what happened based on viewing temporally extended everyday events.

Previous individual differences studies have mostly examined large-scale spatial-memory-from-route experience in the context of other spatial abilities such as mental rotation, perspective taking, maze learning, distance judgments, and sense of direction (e.g., Allen, Kirasic, Dobson, Long, & Beck, 1996; Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006; Kirasic, 2000). For example, these studies have shown large-scale spatial memory is at least partly distinct from factors measured by traditional small-scale spatial tasks (e.g., mental rotation, gestalt completion, hidden figures). Allen et al. (1996) showed that although small-scale abilities predicted memory for large-scale space this relationship was mediated by spatial-sequential memory, a factor driven by maze learning tasks. These results illustrate the importance of learning temporally organized spatial patterns (maze solutions) in constructing large-scale representations from route experience. More generally, it makes sense that temporal order information plays a role in spatial-memory-from-route experience; a reasonably accurate map can be drawn from memory of general route shape and landmark sequence. For example, recollection that a route ended where it began and

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included straight paths, four 90-degree left-hand turns and five landmarks, encountered in a specific order, could support drawing of a fair map even with very limited metric distance information. Despite the apparent importance of temporal processing in large-scale spatial-memory-from-route experience, we are aware of no individual differences studies that have focused on this issue.

Processing of temporal organization is also important for understanding and remembering everyday activities (Zacks, Speer, Swallow, Braver, & Reynolds, 2007). For example, remembering an everyday event such as making breakfast involves organization of the observed activities into the correct temporal order. Bread must be toasted before jam is applied for a specific episodic memory to correspond to a stored script regarding toast making, and such correspondence facilitates episodic memory (e.g., Bransford & Johnson, 1972). A relationship between spatial memory and event memory might be driven in part by the importance of temporal organization for both types of tasks.

There is also evidence from neuroscience suggesting that spatial-memory-from-route experience and memory for everyday events both rely on the hippocampus (Eichenbaum & Cohen, 2014; Schiller et al., 2015). The discovery of place cells and grid cells (Moser, Kropff, & Moser, 2008, for review) and subsequent work (e.g., Wolbers & Buchel, 2005) established the hippocampus's involvement in mental maps of space. However, recent work suggests that the hippocampus supports cognitive maps not only of space, but of time as well (Davachi & DuBrow, 2015; Eichenbaum, 2014; Hsieh, Gruber, Jenkins, & Ranganath, 2014; Mankin, Diehl, Sparks, Leutgeb, & Leutgeb, 2015). An emerging view holds that the map-like properties of the hippocampus result from a more general mechanism of binding items in spatiotemporal context (Ekstrom & Ranganath, 2017). Evidence that the hippocampus codes spatiotemporal context provides another reason to expect that memory for temporally structured events will predict memory for the locations of sequentially encountered landmarks along a route.

One mechanism that may play a role in a relationship between event memory and spatial-memory-from-route experience is *event segmentation*. Research shows that an important part of perceiving and understanding naturalistic events such as making breakfast involves parsing the ongoing flow of activity into meaningful chunks, such as cracking eggs into a bowl and putting toast into the toaster (e.g., Newtson, 1976; Zacks, Tversky, & Iyer, 2001). How people segment events (*event segmentation*) has important consequences for event memory (Boltz, 1992; Ezzyat & Davachi, 2011; Kurby & Zacks, 2011; Newtson & Engquist, 1976; Schwan, Garsoffky, & Hesse, 2000). Because route experiences are themselves events, ongoing segmentation of routes into temporal units might also be important for the formation of structured spatial representations.

There is considerable evidence suggesting that spatial chunking occurs in environmental scale spatial memory (e.g., Hirtle & Jonides, 1985; Wang & Brockmole, 2003). Research on the organization of spatial memory suggests that locations are grouped together on the basis of semantic relatedness (Hirtle & Mascolo, 1986; but see McNamara & LeSueur, 1989), the physical structure of the environment (Allen, 1981; Allen & Kirasic, 1985; McNamara, 1986), and proximity (McNamara, Hardy, & Hirtle, 1989; Sargent, Dopkins, Philbeck, & Chichka, 2010). Objects or landmarks that are associated with each other on the basis of these factors may be remembered as being closer together than objects that are not (or are less strongly) associated. For example, after watching a slide show depicting a walked route through several blocks of a neighborhood, participants identified common boundaries breaking the route up into segments such as a wooded area and a block under construction (Allen & Kirasic, 1985). Subsequent distance estimates showed that remembered distances between landmarks were compressed within segments relative to between segments. Therefore, we included measures of temporal (event) segmentation and spatial chunking in the current study in order to gain a better understanding of how spatial and event memory might be related. It should be noted that temporal structure may not be as consistently reliable in spatial memory as it is for event memory. For example, landmarks that are close together in space may be experienced at disparate time points, and there are types of spatial memory, such as that learned from a map, for which temporal structure may be unimportant. However, due to the ongoing nature of event segmentation mechanisms during everyday navigation activities (Zacks et al., 2007), we hypothesized that event segmentation ability would predict chunking and accuracy in large-scale spatial memory from a route experience.

To test spatial memory for large-scale environments, the current study used a cued map-completion task. Participants watched a route-perspective video shot by a cameraperson walking around a park and then completed an overhead-view map of the park by placing salient landmark icons in their correct locations. The landmarks were placed relative to a line drawing of the path on which the cameraperson walked, which served as the cue in this map-completion task. Sketch mapping tasks, in which participants draw maps of remembered environments, have shown good test–retest reliability (Blades, 1990) and performance on sketch mapping correlates with other measures of environmental knowledge and navigation ability (e.g., Billinghurst & Weghorst, 1995). Cued mapping is used to measure environmental knowledge specifying spatial relationships between landmarks of interest (e.g., Buttenfield, 1986; Kitchin, 1996; Pearce, 1981; Thorndyke & Hayes-Roth, 1982). Individual differences studies reporting exploratory factor analyses of multiple spatial ability measures report that performance on cued map placement tasks such as this one loads squarely on environmental or large-scale spatial factors (Allen et al., 1996; Kirasic, 2000).

The current study used a cued mapping task because it effectively assesses spatial memory based on first-person experiences in which spatial and temporal structure evolve over time. In addition, we chose a task that might encourage the use of configural or survey spatial knowledge. Participants may also have completed the map by relying on knowledge of the route connecting the landmarks rather than relying on a cognitive map specifying the configural layout of the park (Siegel & White, 1975). However, compared with a distance-estimation task such as that used by Allen and Kirasic (1985), completion of a physical map might be more likely to rely on a mental map.

General cognitive factors

The ability to form and use memory for large-scale spaces is complex and involves not just spatial abilities but also non-spatial cognitive abilities (e.g., Wolbers & Hegarty, 2010). For example, superior recollection of the perceptual details from a route experience should improve performance on map-completion tasks independently of cognitive map formation (Ishikawa & Montello, 2006). Therefore, we hypothesized that performance on traditional tests of episodic memory for word lists (*laboratory episodic memory*) would also predict spatial memory.

Working memory—the ability to maintain and manipulate information in a highly accessible state—has also been shown to play an important role in the formation of larger scale environmental representations from route experience (Blacker, Weisberg, Newcombe, & Courtney, 2017; Labate, Pazzaglia, & Hegarty, 2014; Weisberg & Newcombe, 2016). While walking through an environment such as a park, spatial information from successive views must be integrated into an evolving representation built from previous views. Maintenance and updating of this evolving spatial mental model would likely involve working memory. Performance on visuospatial working memory tasks has been shown to predict learning from maps (Coluccia, Bosco, & Brandimonte, 2007), and performance on spatial orientation tasks (Conte, Cornoldi, Pazzaglia, & Sanavio, 1995). Also, adaptive strategy choice (e.g., route based vs. survey based) facilitates performance on mapping and navigation tasks (Hölscher, 2009; Liben, Myers, & Christensen, 2010). Hegarty (2010) has suggested that the executive components of working memory facilitate adaptive strategy choice and therefore are predictive of spatial problem solving generally. In the current study, three complex span tasks (symmetry span, reading span, and operation span) were included to test the hypothesis that domain-general aspects of working memory would predict spatial memory.

Both processing speed (Coyle, Pillow, Snyder, & Kochunov, 2011; Fry & Hale, 1996) and general knowledge (Carroll, 1993; Friedman et al., 2006) correlate with a number of high-level cognitive abilities. In addition, these general cognitive factors are known to interact with age. Age-related declines in processing speed and increases in general knowledge are well established (e.g., Park et al., 1996). Therefore, these factors might be expected to play a role in the relationship between age and spatial memory.

Demographic factors

Age-related differences in spatial memory are well documented (e.g., Cherry & Park, 1993; Cushman, Stein, & Duffy, 2008; Kirasic, Allen, & Haggerty, 1992; Sharps & Gollin, 1987). In particular, older adults are less able than younger adults to acquire, from route experience, configural knowledge necessary for mapping tasks (e.g., Head & Isom, 2010). Thus, age-related differences in spatial memory were expected in the current study. Older adults also have shown specific impairment in the ability to organize features encountered along a route into mental representations that preserve the correct spatiotemporal relationships amongst the features (e.g., Evans, Brennan, Skorpanich, & Held, 1984; Lipman, 1991; Wilkniss, Jones, Korol, Gold, & Manning, 1997). In an individual differences study using extreme groups (old and young), Kirasic (2000) showed that age-related differences in environmental learning were only partly mediated by general spatial ability (e.g., mental rotation), and thus suggested that other, unmeasured factors may also be important in explaining the effect of age on environmental learning. Event memory, laboratory episodic memory, and working memory were all expected to predict spatial memory, and have been shown to be worse in older adults than in younger adults (e.g., Kurby & Zacks, 2011; Park et al., 1996; Zacks, Speer, Vettel, & Jacoby, 2006). The current study is the first to consider these potential mediators of the relationship between age and spatial memory in a continuous adult life-span sample.

Research on gender differences in spatial ability has shown mixed results. For example, males have shown greater accuracy in fine-grained, metric spatial memory and in route memory (Gron, Wunderlich, Spitzer, Tomczak, & Riepe, 2000; Lawton, Charleston, & Zieles, 1996; Postma, Jager, Kessels, Koppeschaar, & van Honk, 2004) while women have shown advantages in associating certain objects with certain locations (e.g., Eals & Silverman, 1994). Both types of abilities are likely to be important for large-scale spatial memory based on route experience. In large-scale environmental learning contexts, there is evidence that males tend to rely on survey or configural representations, whereas females rely more on route representations (Lawton, 1994; Lawton et al., 1996; Montello, Lovelace, Golledge, & Self, 1999). Therefore, one might expect males to perform better on a map-completion task. However, the provision of the cue (path drawing) in the current study may have encouraged the use of route-based representations. Other studies have shown no gender differences on large-scale spatial-memory-from-route experience (Allen et al., 1996; Kirasic, 2000) or have found that gender differences in spatial layout learning were mediated by a self-reported sense of direction and small-scale spatial ability tests (Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006). The current data set allowed us to examine the relationship between gender and large-scale spatial memory based on route experience in the context of (nonspatial) psychometric factors. For example, females have been shown to perform better on laboratory tests of episodic memory (e.g., Lewin, Wolgers, & Herlitz, 2001; Zelinski, Gilewski, & Schaie, 1993), which we hypothesized would contribute to large-scale spatial memory based on route experience. Thus, it is possible that superior episodic memory abilities amongst females provide an advantage on tests of spatial memory.

To summarize, the current individual differences study extends previous work by focusing on novel, nonspatial factors such as temporal processing ability and event memory that contribute to spatial-memory-from-route experience in a sample of adults ranging in age from the 20s to the 70s. Specifically, the primary hypothesis in the current study was that memory for temporally extended naturalistic events (event memory) would explain unique variance in large-scale spatial memory based on route experience. Secondary hypotheses were that (1) event segmentation would predict spatial memory accuracy and chunking in spatial memory; (2) memory for word lists and (3) working memory would also predict spatial memory; and (4) spatial memory would be less accurate in older adults, and this relationship would be mediated by general, nonspatial cognitive abilities. Although we had no specific hypotheses about gender effects, in exploratory analyses we searched for mediators of potential gender differences in spatial memory.

Method

These data came from a larger study of event perception and memory. Details of the participant population and general methods are also reported in Sargent et al. (2013; see also Eisenberg, Sargent, & Zacks, 2016). The sample consisted of 208 adults (102 females), 17–18 of each gender from each decade of life, 20s through 70s.[1] Participants were recruited from the St. Louis, MO (USA) community as part of a project examining event segmentation and memory across the life span. Participants received $10 per hour compensation.

[1] In all, 233 adults were recruited, but 25 were excluded for missing the second of two sessions ($n = 8$), failing to meet criteria on the dementia screens ($n = 9$), failing to segment at least two of the everyday event movies ($n = 5$), failing to follow instructions ($n = 1$), or experimenter error ($n = 2$).

Large-scale spatial memory from route experience—cued-map placement task

Participants were seated approximately 60 cm from a 50-cm LCD monitor and viewed a video (252 s) depicting a navigation episode through an urban park. The video was shot with a stabilized hand-held camera by a researcher walking around the perimeter of the park. The video started and ended at the south end of the park, looking north, with a shot that panned across the entire park (see Fig. 1a).

Fig. 1 Still frames from the movie used in the spatial-memory-from-route experience task, converted from color to grayscale. Onscreen labeling of the target objects is demonstrated in **b**

When the cameraperson was walking, the camera was primarily pointed in the direction of travel, but occasionally panned in toward the middle of the park to mimic the head movements of someone exploring the park for the first time. During the video, nine target objects were labeled on the screen (for approximately 2 s each) and named in a voiceover as the camera moved past them (see Fig. 1). Prior to viewing the video, participants were told that their spatial memory would be tested; they were also told to pay attention to the video and try to remember the locations of the identified objects. The video is available in the online supplemental materials.

After the video ended, each participant was given a response map showing an overhead-view line drawing of the path on which the cameraperson walked as they shot the movie (see Fig. 2b). The response maps, printed on 28 × 43-cm white paper, showed only the path, not the correct locations. The response map was oriented so that participants' perspectives were aligned with that of the camera at the beginning and end of the video. The start point, end point, and direction of travel were indicated by an experimenter (but were not printed on response maps). Participants were given line drawings of the nine target objects (icons) printed on round pieces of paper approximately 1.3 cm in diameter. The icons were also labeled with the object names used in the video. Participants were instructed to arrange the icons so as to create an accurate overhead view of the park (see Fig. 2). There was no time limit. Participants were provided with the path (cue) in the current study in order to reduce individual differences in performance that might arise from differences in scale. For example, if maps were too small, the size of the icons would make it physically difficult to place them accurately. Icons were provided, rather than asking participants to draw the remembered landmarks in, because we wanted to exclude variability in performance due to drawing or object identity recall abilities.

Performance on the cued map placement task was assessed two ways: as Euclidean error and using bidimensional regression. To measure Euclidean error, for each participant, the distances (mm) the icons were placed from their correct locations were averaged together across the nine target objects. In the current paradigm, the "blank" response maps showed the

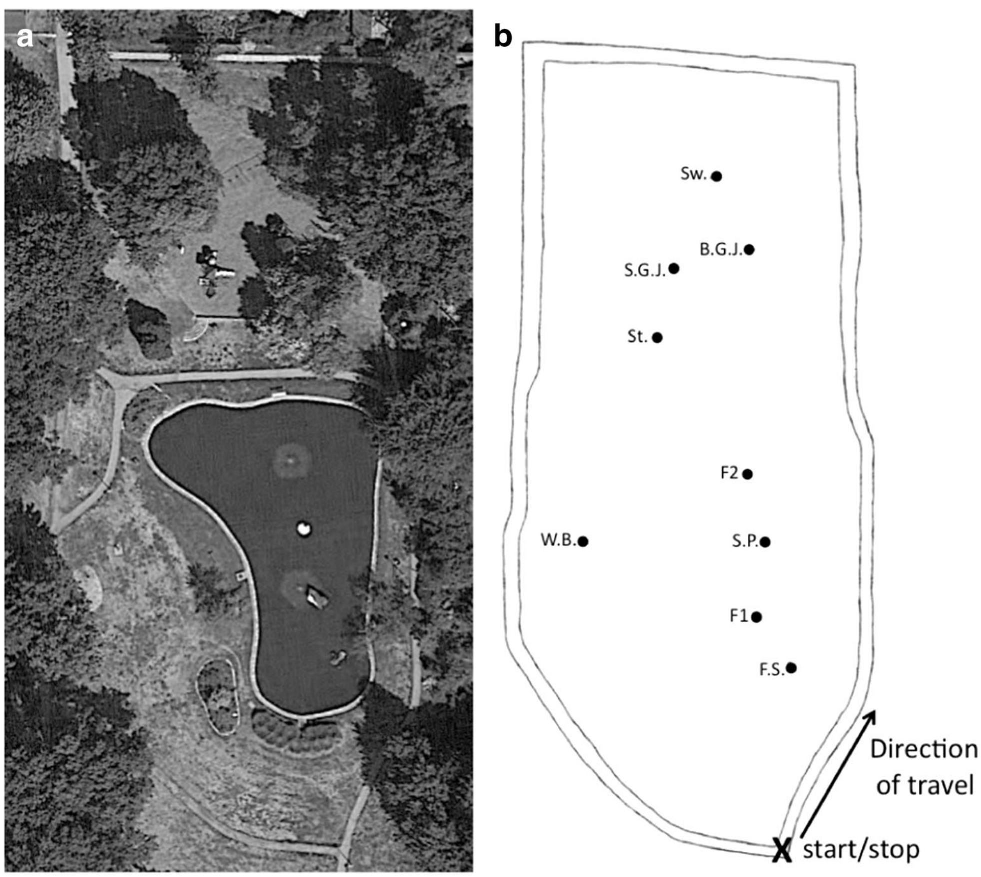

Fig. 2 Satellite photo from Google Inc. (2009) of the park used in the spatial-memory-from-route experience task is shown in **a**. Overhead view line drawing of the path on which the cameraperson walked, with the correct object locations is shown in **b**. Response sheets used by the participants were blank except for the line drawing of the path shown in **b**. Objects were named in the video in the following order: F.S. = fish sculpture; F1 = fountain1; S.P. = stone pedestal; F2 = fountain2; B.J.G. = big jungle gym; Sw. = swings; S.J.G. = small jungle gym; St. = stairs; W.B. = water bubbler

path on which the cameraperson walked as they shot the movie (see Fig. 2b) and this could be used to determine the correct absolute locations on the response sheet. Euclidean error includes error in the remembered spatial relationships between the target objects and the walked path. In order to exclude this source of error we also ran a bidimensional regression analysis (Tobler, 1965). Bidimensional regression provides a measure of correspondence between two maps, or sets of bidimensional (e.g., *x, y*) coordinates, after accounting for differences in scale, translation, and rotation. Thus, we were able to measure memory for the interrelationships among the target objects, regardless of scale or how the array was placed or oriented on the response sheet. We treated the actual target object locations as the independent variable and the remembered locations as the dependent variable (Friedman & Kohler, 2003). If *XY* are the coordinates of an individual's cognitive map, and *X'Y'* are the coordinates predicted by the bidimensional regression model, then distortion distance (D) $= \sqrt{\sum [(X - X')^2 + (Y - Y')^2]}$. Distortion index (DI) scales D by the total amount of error possible [DI = 100 (D/D_{MAX})] (Waterman & Gordon, 1984). We used distortion index (DI) as the primary outcome measure because it can be directly compared to DI scores from other studies that may have used different maps with, for example, different numbers of landmarks.

Spatial chunking In order to measure chunking in the map placement task, we chose target objects in the park that could objectively be organized into two groups. Examination of Figs. 1 and 2 reveals a pond group (fish sculpture, Fountain 1, stone pedestal, Fountain 2, water bubbler), and a playground group (big jungle gym, swings, small jungle gym, stairs). Several factors suggest this grouping of the target objects. First, most of the objects in each group are semantically associated with either pond or playground. Second, the park is bisected by a path that can be seen running horizontally in Fig. 2a between the two groups of targets. Third, in the video, the pond objects were named sequentially first (except for the water bubbler, which was named last), and then all the playground objects were named sequentially. Elapsed time was, on average, 17 s between the naming of targets from the same group and 27 s between targets in different groups. Finally, an agglomerative hierarchical cluster analysis based on squared Euclidean distance between target objects supported the existence of the two (pond and playground) groups, or chunks.

In order to capture a variety of error patterns that might be indicative of spatial chunking, we used a modified bidimensional regression analysis to produce a strength-of-chunking variable. The fit between each participant's completed response map and the veridical map was determined two ways: using traditional bidimensional regression (Tobler, 1965) and using a modified bidimensional regression equation that allowed for separate rigid transformations to be applied to each of the two previously identified chunks independently. Details of this modified bidimensional regression are reported in the Appendix. For each participant, an *F* test can be established comparing the two regression models, M_0 without chunking, and M_1 with chunking: $F = ((SSE_0 - SSE_1)/\Delta df)/(SSE_1/df_1)$, where $\Delta df = df_0 - df_1$, $df_0 = 2n - 4$, and $df_1 = 2n - 8$. Under the null hypothesis that there is no chunking effect, the test statistic follows an *F* distribution with degrees of freedom Δdf and df_1, and a median of approximately 1.

Event segmentation and event memory

Participants viewed three movies, each showing an actor engaged in an everyday activity and lasting approximately 5 minutes. Movies were shot from a stationary, head-high perspective and involved no zooming. One movie showed an actor preparing breakfast in a kitchen, another showed an actor decorating and preparing a dining room for a party, and the third movie showed an actor planting flowers in window boxes on the outside of a brick house. Participants were asked to segment each movie by pressing a key in order to indicate where they judged that one meaningful unit of activity had ended and another had begun (e.g., Newtson, 1976). Participants were instructed to identify the largest units they found meaningful (coarse segmentation) on their first viewing, and the smallest units they found meaningful (fine segmentation) on their second viewing. Before both coarse and fine grain segmentation, participants practiced segmenting a movie of an actor building a boat out of toy blocks (duration 155 s). If they identified fewer than three coarse or six fine grain event boundaries, participants were asked to identify "a few more" units, and the practice movie was repeated.

Following previous studies (e.g., Kurby & Zacks, 2011; Zacks et al., 2006), *segmentation ability* was defined as the degree to which an individual agreed with the sample as a whole about where event boundaries occurred in the movies. To create a segmentation norm for the sample, we divided each movie into 1-second bins and calculated the proportion of participants that identified a boundary within each bin. We then coded each participant's segmentation using the same 1-second bins. For each participant and movie, we calculated the correlation between the individual's segmentation and the group norm. The correlations were scaled for each participant based on the highest and lowest correlations possible given the number of boundaries identified, resulting in a segmentation ability score with a range from zero to one (Kurby & Zacks, 2011). This approach adduces a performance measure from an inherently subjective task by using normative segmentation as a standard. Although the event segmentation instructions are subjective, in practice event segmentation has been shown to be strongly related to physical stimulus features (e.g., Hard, Recchia, & Tversky, 2011; Newtson, Engquist, & Bois, 1977; Zacks, 2004; Zacks, Kumar, Abrams, & Mehta, 2009; Zacks, Speer, & Reynolds, 2009) and has been shown to have construct validity in that it predicts subsequent event memory (Flores, Bailey, Eisenberg, & Zacks, 2017; Sargent et al., 2013).

Both fine-grained and coarse-grained segmentation were collected in order to examine the extent to which events of longer and shorter duration might be hierarchically arranged. However, this was not a focus of the current study. Therefore, and because fine-grained and coarse-grained segmentation ability scores were highly correlated ($r = .64$), they were averaged together for each participant prior to analysis.

To test event recall, participants were given 7 minutes to write or type, in as much detail as possible, what happened in the movie they just watched. For each movie, we constructed a list of the basic actions performed by the actor, using criteria described by Schwartz (1991; termed "A-1" units therein). Event recall scores were the number of correctly recalled actions (interrater kappa = 0.84 [$p < .001$], 95% CI [0.78, 0.90]). After the recall test, order memory was tested. [2] Participants were given 12 randomly ordered still frames from the movie, each printed on a 10-cm × 15-cm card, and asked to arrange them in the order in which they appeared in the movie. Order memory was scored with an error measure: how far on average were the cards placed from their correct sequential positions.

General cognitive abilities

The general cognitive battery included three established measures for each of the following constructs: working memory, laboratory episodic memory, processing speed, and general knowledge.[3] Three measures were used for each construct in order to minimize task-specific variability and assess individual differences in the underlying constructs. In addition, two dementia screens were completed.

Working memory was assessed with complex span tasks (operation span, reading span, and symmetry span) that measure how many items can be held in mind while cognitive resources are taxed by concurrent processing tasks (Turner & Engle, 1989). For reading span (RSpan), on each trial a sentence appeared, and participants judged whether it made sense or not (concurrent processing task), then a-to-be-remembered letter appeared, then another sentence, another letter, and so forth, and finally the letters were recalled. Operation span (OSpan) was the same, except instead of sentence judgments, participants performed simple math problems for the processing task. For symmetry span (SSpan), the processing task is making symmetry judgments about patterns of squares, and the to-be-remembered items are locations on a grid. Scores reflect total number of items recalled, excluding those for which performance on the corresponding processing task was incorrect.

Laboratory episodic memory was tested using a selective reminding test, a verbal paired associates task, and a word list recall task. In the selective reminding test (Buschke, 1973), participants were presented with 16 line drawings of objects on paper and asked to point out each object when named by an experimenter. After each of four free recall attempts (except the last), participants were reminded of the objects they missed. The final attempt occurred after a delay (filled with other cognitive tasks) of approximately 30 minutes. In the verbal paired associates task (Wechsler, 1997), participants were read eight word pairs aloud, and then given the first word of each pair as a cue to recall the second. Four trials were completed, the final trial included a 30-minute filled delay. The word list recall task (Small, Dixon, Hultsch, & Hertzog, 1999) entailed two trials, in each of which participants were required to study a list of 30 words, printed on paper, for 2 minutes and then immediately recall and write down as many as possible for up to 5 minutes. Performance on laboratory episodic memory tests was scored as the total number of items recalled across all attempts.

Processing speed tasks (shape, letter, and pattern comparison) measured the rate at which visually presented stimuli could be differentiated. In shape comparison (Chen, Hale, & Myerson, 2007), one comparator and two choice shapes were presented on a computer screen simultaneously, and participants chose by button press which of the two choice shapes matched the comparator. Mean reaction time was measured. In letter and pattern comparison tasks (Salthouse & Babcock, 1991), a page of letter string or pattern pairs was presented, and participants indicated if each pair was the same or different by writing an "S" or "D" on the line between them. The number of correct comparisons made in 20 seconds was recorded.

General knowledge was assessed by multiple-choice vocabulary tests in which participants chose the synonyms or antonyms of presented words (Wechsler, 1997) and by general information questions such as "Who was Cleopatra?" (Salthouse, 1993). Two dementia screens were also used to assure a cognitively normal sample, the Short Blessed Test (SBT; Katzman et al., 1983) and a brief, self-administered Alzheimer's disease (AD) screen, the AD8 (Galvin et al., 2005). The AD8 was designed to be more sensitive to early-stage dementia than the commonly used Mini-Mental State Examination (MMSE).

[2] A recognition memory test was administered for each movie after the recall test, and before the order test. Because reliability for the recognition test across the three movies was low ($\alpha = .47$), and because we had no theoretical reason to predict a relationship specifically between recognition and spatial memory, the recognition measure is not included here.

[3] Three tests of executive function were also administered as part of the current study; however, a confirmatory factor analysis showed that they did not form a latent variable (see Sargent et al., 2013) and so executive function is not included in the current analyses.

Procedure

Each participant completed two 150-minute testing sessions that took place on different days, no more than a week apart. Each session began with the event segmentation tasks (coarse segmentation in Session 1 and fine segmentation in Session 2). The event memory tasks were completed immediately after watching and segmenting each movie in the first session only. After the event segmentation and memory tasks, the general cognitive battery was administered in the following order: In Session 1, participants completed reading span, operation span, symmetry span, shape comparison, and synonym and antonym vocabulary tasks. In Session 2, after segmenting all three movies at a fine grain, participants completed the remaining psychometric measures and the SBT dementia screen. The cued map placement (spatial memory) task lasted approximately 10 minutes and was completed in the latter half of the second session. Between Sessions 1 and 2, participants completed the AD8 and a brief questionnaire covering demographic information.

Results

To screen for outlying observations, we marked values over 3.5 standard deviations from the total sample mean. We replaced the 15 values that met this criterion (.2% of the data), along with 45 missing values (.7% of the data), using the expectation maximization (EM) procedure in SPSS 19.0. The variables were approximately normally distributed (|skewness| < 2.0, |kurtosis| < 2.0). Descriptive statistics for males and females are presented in Table 1. The only clear gender differences were that females outperformed males on all the episodic memory measures (see Table 1). The correlation matrix (see Table 2) shows that almost all the variables

Table 1. Descriptive statistics by gender

Construct	Measure	Females (n = 102) *M* (*SD*)	Males (n = 106) *M* (*SD*)	*t*	All (n = 208) Range
Spatial memory					
	Euclidean error	52.49 (22.06)	50.36 (22.85)	.69	11–128
	Distortion index (DI)	43.00 (22.3)	41.55 (22.51)	.47	8–99
Event memory					
	Event recall mem.	28.81 (11.76)	24.33 (10.84)	2.86**	1.7–59
	Event order mem.	.76 (.61)	.74 (.65)	.22	0–2.5
Event segmentation					
	Segmentation agreement	.59 (.09)	.59 (.09)	.61	.30–.75
Working memory					
	Reading span	20.23 (6.10)	19.97 (6.36)	.31	0–28
	Operation span	19.20 (6.89)	20.33 (7.07)	−1.17	3–28
	Symmetry span	11.46 (6.66)	12.51 (5.99)	−1.20	0–28
Laboratory episodic memory					
	Selective reminding	47.49 (6.79)	45.45 (7.31)	2.08*	24–62
	Verbal paired ass.	18.89 (3.59)	17.33 (4.19)	2.87**	6.5–25
	Word list recall	18.43 (5.44)	16.75 (5.52)	2.22*	4.5–29
Processing speed					
	Shape comparison	1.00 (.27)	.99 (.27)	.20	.5–1.8
	Letter comparison	6.98 (1.84)	7.03 (1.90	−.20	3–12.5
	Pattern comparison	12.62 (2.94)	12.83 (2.69)	−.54	6–22
General knowledge					
	Synonym vocabulary	.55 (.31)	.52 (.28)	.53	0–1
	Antonym vocabulary	.52 (.29)	.51 (.29)	.40	0–1
	Information test (WAIS)	17.15 (5.94)	18.95 (5.43)	−2.28*	4–27
Spatial chunking					
	F statistic	1.67 (1.62)	1.70 (1.80)	−.12	.04–14

Scores are proportion correct except as follows: span scores = total number of items recalled for which corresponding processing task was correct; letter/pattern comparison = items completed in 20 s; shape comparison = average time in s to complete one trial. Spatial memory, event memory, segmentation agreement and spatial chunking are described in the Methods section

$^*p < .05$. $^{**}p < .01$. $^{***}p < .001$

Table 2. Correlations between variables

Variable		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	EucEr	–																	
2	DI	.79	–																
3	Age	.19	.18	–															
Event memory/Segmentation																			
4	ERec	−.43	−.49	−.13	–														
5	EOrd	.35	.41	.24	−.45	–													
6	Seg	−.29	−.31	−.07	.49	−.38	–												
Working memory																			
7	RSpn	−.35	−.34	−.12	.54	−.44	.39	–											
8	OSpn	−.28	−.31	−.16	.41	−.45	.37	.72	–										
9	SSpn	−.37	−.44	−.43	.44	−.50	.29	.51	.50	–									
Laboratory episodic memory																			
10	SRem	−.23	−.33	−.34	.32	−.33	.22	.30	.26	.36	–								
11	VPA	−.29	−.38	−.41	.41	−.34	.24	.34	.31	.44	.49	–							
12	WL	−.41	−.50	−.07	.63	−.45	.44	.58	.48	.40	.44	.47	–						
Processing speed																			
13	Shp	.26	.33	.55	−.32	.30	−.24	−.24	−.21	−.43	−.38	−.34	−.28	–					
14	Let	−.30	−.38	−.40	.48	−.40	.26	.43	.47	.50	.45	.45	.50	−.52	–				
15	Pat	−.30	−.36	−.54	.39	−.28	.23	.36	.40	.48	.39	.34	.39	−.58	.62	–			
General knowledge																			
16	Syn	−.15	−.22	.41	.37	−.21	.17	.38	.31	.04	.02	.15	.46	.10	.14	−.02	–		
17	Ant	−.13	−.21	.31	.34	−.25	.13	.34	.26	.08	.03	.16	.44	.10	.17	.03	.77	–	
18	Inf	−.28	−.37	.27	.41	−.38	.31	.41	.41	.22	.08	.23	.52	−.01	.24	.08	.70	.67	–
19	SpCh	.05	.02	.07	−.05	.00	.04	.05	.04	−.06	.08	.01	.06	.06	−.08	−.08	.17	.09	.11

N = 208. EucEr = Euclidean map error; DI = distortion index map error; ERec = event recall memory; EOrd = event order memory; Seg = event segmentation; RSpn = reading span; OSpn = operation span; SSpn = symmetry span; SRem = selective reminding; VPA = verbal paired associates; WL = word-list memory; Shp = shape comparison; Let = letter comparison; Pat = pattern comparison; Syn = synonym vocabulary; Ant = antonym vocabulary; Inf = information test; SpCh = spatial chunking. Threshold value for $p = .05$ is $r = .14$; for $p = .01$ is $r = .18$; and for $p = .001$ is $r = .23$

measured were at least moderately correlated with error scores from the map-placement task. The variables hypothesized to contribute to spatial-memory-from-route experience (event memory, word-list recall, and working memory, particularly spatial span) showed the strongest zero-order correlations with spatial memory (see Fig. 3).

Visual inspection of the pattern of bias in remembered target locations across all participants (see Fig. 4) reveals no clear organization of spatial memory into the anticipated (pond and playground) chunks. Specifically, in the aggregated data, there is no obvious systematic bias toward respective chunk centroids, or any clear rotational or translational rigid deformations that occurred independently for the pond or playground chunks. However, the modified bidimensional regression analysis detailed in the Method section suggests that such chunking occurred. The correspondence of each subjects' reconstructed map with the actual map was calculated using two models, a chunking model and a no-chunking model. The relative fit of these models was compared by calculating an F statistic for each participant (see Method section). A one-sample Wilcoxon signed rank test showed that the median F statistic across participants (1.24) was greater than one ($p < .001$); on average, the chunking model fit the data better than the no-chunking model.[4] The measure of spatial chunking (F statistics) correlated near zero with all other measures (see Table 2), so we omitted spatial chunking from further analyses.

[4] A simulation analysis was run to bolster this conclusion. Map error was selected at random from normal distributions, separately for x and y dimensions ($M = 0$, SDs were based on those observed in actual data), for each object, for each of 1,000 simulated participants. The signed rank test showed that the median F statistic across participants was not greater than one ($p > .05$). Essentially, we generated map data in which angular and directional error for each object was randomly determined (no systematic chunking) and observed that the chunking model did not show significantly better fit than standard bidimensional regression. This suggests that the difference observed in the data was not due merely to mathematical properties of the two models.

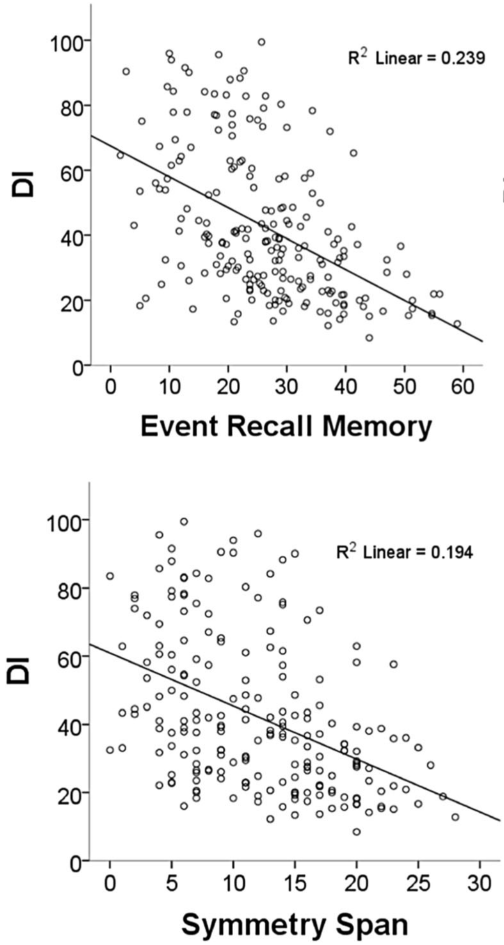

Fig. 3 Scatterplots showing strongest relationships between spatial memory (DI) and other measures

Regression analyses

We used multiple linear regression to determine which general cognitive abilities, event processing abilities, and demographic factors were uniquely predictive of cued map-placement error. The correlation matrix in Table 2 shows that the *general cognitive ability* variables correlated positively with each other, as expected. Furthermore, the variables representing each general cognitive ability construct tended to correlate more strongly with each other than with the other variables, and composite variables created by averaging *z* scores for measures within each construct had good internal consistency reliability (αs > .70)[5]. Sargent et al. (2013) performed confirmatory factor analyses (CFAs) to establish measurement models with latent variables representing the general cognitive ability constructs (WM capacity, laboratory episodic memory, perceptual speed, and general knowledge [Gc]) with three indicators per construct (see General Cognitive Abilities in the Method section). Those results are summarized here. The CFAs included a correlated error for operation span and reading span (*r* = .42), given that these tasks had the same memoranda, and a cross-loading from Gc to word-list memory, based on the results of a preliminary exploratory factor analysis. The factors loaded as expected on the constructs as follows. Loadings for RSpan, OSpan, and SSpan onto working memory were .70, .74, and .70, respectively. Loadings for selective reminding, paired associates, and word-list memory onto laboratory episodic memory were .68, .67, and .62, respectively. Loadings for letter, pattern and shape comparison onto processing speed were .80, .79, and −.68, respectively (the first two were scored as problems completed within time limit, whereas shape comparison was scored as RT). Finally, loadings for synonym, antonym vocabulary, and general information tests onto general knowledge were .89, .85, and .80, respectively. All other loadings were set to zero. The fit for this model was good, $\chi^2(46) = 106.78$, $p < .01$, CFI = .95, NFI = .92, RMSEA = .08. Working memory, laboratory episodic memory, and processing speed factors were all highly correlated with each other (*r*s between .75 and .78), while general knowledge correlated less strongly with the other factors (*r*s below .42). In order to simplify the following regression

[5] The exception was order memory which showed weak item-level reliability across the three event movies (α = .50).

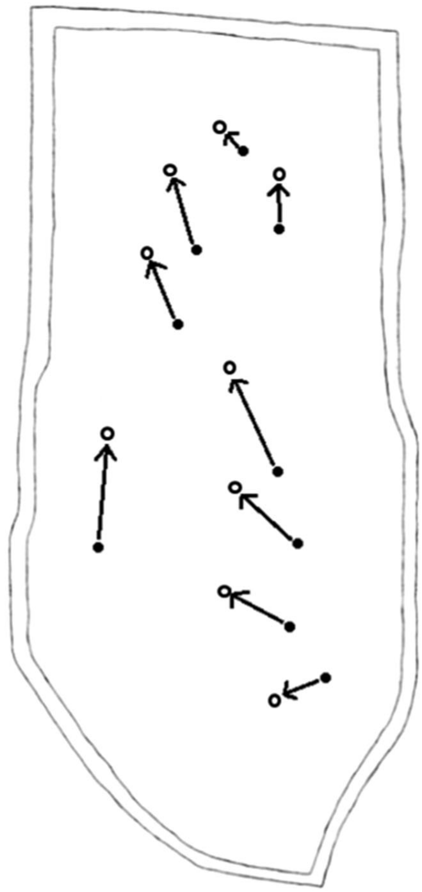

Fig. 4 Median bias in remembered target object locations across participants. Filled dots are actual object locations; arrows point to respective remembered locations (unfilled dots)

analyses and to conserve degrees of freedom, these composite factors were used as predictor variables.

For each of the three event-processing variables, event recall, order memory, and segmentation ability, each participant's score was calculated as the average across the three different event movies (breakfast, party, and planters). Item-level reliability across the three movies was good for event recall ($\alpha = .78$) and segmentation ability ($\alpha = .86$), but not for order memory ($\alpha = .5$). Therefore, the full regression results reported below omit order memory. However, because temporal processing is hypothesized to be important for the relationship between event and spatial memory, regressions were also run with order memory as a predictor. Results regarding order memory are reported but are not shown in tables and should be interpreted cautiously.

Euclidean error We regressed Euclidean error onto age, gender, education, event memory, event segmentation, working memory, laboratory episodic memory, processing speed, and general knowledge (results are shown in Table 3). Together, the predictors accounted for 26% of the variance in spatial memory, with a significant unique contribution from event memory and a marginally significant unique contribution from gender (p = .062). In a hierarchical regression model, we entered all the predictor variables above, except for event memory in Step 1, and then added event memory in Step 2; event memory alone accounted for 3.2% of the variance in Euclidean error, and the relationship was in the direction of lower Euclidean error with increasing event memory. Gender uniquely accounted for 1.3% of variance in spatial memory; males showed lower Euclidean error than did females. Controlling for all other the variables we measured, participants who recalled more details from movies depicting everyday activities produced more accurate maps. However, event segmentation (segmentation agreement) did not predict map accuracy. When order memory was included as a predictor variable, it did not uniquely predict variance in Euclidean error, nor did it change results for the other predictor variables.

Table 3. Multiple regression analysis predicting Euclidean error in map reconstruction task

	R^2	F	df	β	t
Total	.256	7.57**	9, 198		
Age				.082	.91
Gender (0 = f, 1 = m)				−.126	−1.88
Education				−.015	−.21
Event recall memory				−.264	−2.94**
Segmentation agreement				−.062	−.85
Working memory				−.093	−1.06
Laboratory episodic memory				−.140	−1.52
Processing speed				−.012	−.13
General knowledge				−.024	−.26

N = 208. *p < .05. **p < .01

Distortion index (DI) We regressed DI onto the same predictors used above (the results are shown in Table 4). Together, these

Table 4 Multiple regression analysis predicting distortion index (DI) in map reconstruction task

	R^2	F	df	β	t
Total	.36	12.22**	9, 198		
Age				−.001	−.01
Gender (0 = f, 1 = m)				−.132	−2.11*
Education				.082	1.20
Event recall memory				−.241	−2.87**
Segmentation agreement				−.029	−.43
Working memory				−.047	−.57
Laboratory episodic memory				−.263	−3.08**
Processing speed				−.121	−1.38
General knowledge				−.119	−1.42

N = 208. *p < .05. **p < .01

variables accounted for 36% of the variance in spatial memory, with significant unique contributions from laboratory episodic memory, event memory, and gender. Hierarchical regression models showed that laboratory episodic memory and event memory uniquely accounted for 3.1% and 2.7% of the variance in DI, respectively. Gender uniquely accounted for 1.4% of variance in DI. Again, better episodic memory and being male was associated with better spatial memory, but event segmentation was not associated with spatial memory at all. When order memory was included as a predictor variable, it uniquely predicted marginally significant variance (1.2%) in DI, $\beta = .14$, $t(197) = 1.97$, $p = .05$. Event recall laboratory episodic memory and gender remained the only other significant predictors of DI after the inclusion of order memory in the model.

Discussion

We measured the ability of 208 adults of varying age to recall the layout of an environment after route experience. A battery of nonspatial cognitive tests was also administered in order to identify abilities that contribute to this spatial memory task. Tests of episodic memory were the strongest predictors of map completion after route experience. Of particular interest, memory for everyday activities predicted spatial memory above and beyond demographic (age and gender) and all other cognitive ability factors measured, including episodic memory as typically measured in the laboratory (using lists of words and pictures as memoranda). In addition, we found evidence of chunking in spatial memory, but the tendency to chunk had no correlation with spatial memory performance, temporal chunking, or any other variable we measured.

We hypothesized that the relationship between the type of spatial memory studied here and event memory is driven by the importance of temporal organization for both. This hypothesis received limited support. The ability to temporally parse naturalistic activity in a way that reflects inherent structure (segmentation ability) did not predict a tendency to produce maps organized into chunks (spatial chunking). It is possible that the influence of temporal organization on spatial memory is reflected in a form of spatial organization other than chunking, such as the influence of axes, boundaries, or linear order. Temporal segmentation ability also failed to predict map accuracy (also see Richmond, Sargent, Flores & Zacks, 2018). This null result does not rule out a relationship between processing of temporal structure and constructing large-scale spatial memory, but it does suggest that the perception of normative event boundaries, specifically, is not central to this relationship. So what is? Even though our measure of event order memory showed poor item-level reliability across the three event movies and should thus be interpreted cautiously, it correlated with performance on the spatial memory task ($r = .41$) more strongly than did segmentation ability; and when added to the regression analysis reported in Table 4, it uniquely accounted for marginally significant ($p = .050$) variability in spatial memory. This provides limited evidence that the processing of simple sequential information contributes to spatial-memory-from-route experience, which is consistent with previous individual differences studies of spatial ability (Allen et al., 1996). In fact, the Sobel test showed that order memory was a significant mediator ($z' = 3.31$, $p < .001$) of the zero-order relationship between event recall and spatial memory (r dropped from −.49 to −.37), suggesting that temporal order processing may be a specific mechanism driving the unique relationship between event memory and spatial-memory-from-route experience.

Memory for temporally structured events may also uniquely predict spatial-memory-from-route experience because both are particularly dependent not only on temporal relationships but also on relational information more generally. Clearly, recall memory in general, including recall of word lists, involves relational processing (e.g., Polyn, Norman, & Kahana, 2009). However, event and spatial memories include additional dimensions in which relationships can be represented. For example, in addition to the ways words on a list are related (e.g., semantically and by temporal proximity), bits of activity within larger events and individual object locations also have very salient causal and spatial relationships, respectively. These dimensions provide substrates for potentially richer relational (e.g., hierarchical, conditional) knowledge structures. Our results are consistent with reliance of spatial, temporal and other (causal, semantic, etc.) associations on a common associative processor, the hippocampus (Schiller et al., 2015).

Of course, non-relational general memory processes, such as rote memorization, may also contribute to spatial memory. In regression analyses, laboratory episodic memory (measured as memory for lists of words, word pairs and pictures) predicted unique variance in spatial memory as measured by DI (see Table 4). In the current study, there was considerable overlap between the laboratory episodic and spatial memory tests in how the test items were presented. Recall that the target objects were identified during the route experience by the appearance of a word on the screen and a voiceover, both naming the object. Thus, the ability to remember—perhaps by rote—a list of unambiguous, discrete verbal codes (words) might explain shared variance between our laboratory episodic and spatial memory tests.

Although the three working-memory span tasks all correlated with spatial memory (see Table 2), the latent, domain-general working memory construct did not predict the spatial memory measures after controlling for the other variables measured. This is somewhat surprising given the apparent importance of working memory for the construction large-scale spatial memory from extended route experiences (Blacker et al., 2017; Weisberg & Newcombe, 2016). However, Hegarty et al. (2006) found that spatial span tasks were stronger predictors of map-completion tasks than were nonspatial span tasks, and this fits with current results. If the working memory composite variable is broken up and the three span tasks are entered into the regression shown in Table 4 separately, the spatial span task does predict unique variance in spatial memory as measured by DI, $\beta = .28$, $t(196) = -2.48$, $p < .05$. This is consistent with evidence that forming large-scale spatial memories from route experience relies mainly on aspects of working memory that are specific to spatial processing (Labate et al., 2014; Wen, Ishikawa, & Sato, 2011, 2013).

The unusually weak correlations observed between age and some of the episodic memory measures, including the spatial memory test (see Table 2), may have resulted from sampling bias. We seem to have captured a relatively high performing group of older adults (see Sargent et al., 2013, for details). However, as predicted, the small zero-order relationship we did observe between age and spatial memory was completely mediated by other, nonspatial variables included in the regression and structural equation models. This suggests that we captured some general cognitive mediators of the age environmental learning relationship that are not typically included in individual differences studies of spatial ability (Kirasic, 2000).

On both of the spatial memory measures, males performed numerically better than females. This difference approached statistical significance in the multiple-regression models. There was a significant gender difference in laboratory episodic and event memory tasks, with females significantly outperforming males. This is consistent with previous work showing superior episodic memory performance among females, especially for verbal material such as that used in the present tests of laboratory episodic memory (e.g., Lewin et al., 2001; Zelinski et al., 1993). Superior event memory amongst females, for everyday activities depicted in videos, is an interesting finding that extends previous work showing better episodic memory amongst females not just for verbal material, but more generally (e.g., Herlitz, Nilsson, & Bäckman, 1997; Hultsch, Masson, & Small, 1991). In these data, episodic memory ability appears to be a suppressor of the effect of gender on spatial memory, because the simple pairwise tests of the effect of gender on spatial memory were not significant. The advantage for males seen here may reflect demonstrated advantages in metric, configural, or small-scale spatial abilities (e.g., Hegarty et al., 2006; Lawton et al., 1996; Postma et al., 2004) that likely contribute to large-scale spatial-memory-from-route experience. However, these differences were compensated for by females' superior verbal and general episodic memory abilities, which we have shown are also important for large-scale spatial-memory-from-route experience.

A novel analysis showed some evidence that mental representations of navigable environments are organized into chunks of related landmarks and that this organization influences how spatial memory is used to construct maps. This is consistent with previous work designed to reveal the organization of spatial memory (Allen & Kirasic, 1985; Hirtle & Jonides, 1985). The current analysis extended this effort by looking for evidence of chunking as bias toward chunk centroids, chunk translation, and chunk rotation all in one quantitative, continuous measure that can be calculated for each participant (or map) and scales with the degree of chunking. We anticipated that this individual-differences measure of tendency to chunk would shed light on the mechanisms and usefulness of spatial chunking through its relationships with other variables, but no such relationships were observed. Spatial chunking may be domain specific and thus independent of the general cognitive factors we measured. However, spatial chunking presumably serves, like chunking more generally, to compress to be remembered material, and thus make that material easier to remember. If this is true, the current paradigm failed to capture the memory advantage related to chunking; chunking did not predict map accuracy. Although we saw evidence of chunking in the current paradigm, perhaps the *benefit* of chunking only manifests at longer delays, or with larger maps, or in different spatial tasks. It is also possible that our route experience video did not contain cues to spatial segmentation that were strong, salient, or controlled enough. These speculations might be tested in future work, but current data do not support the functional significance of chunking in memory for large-scale spaces.

Future investigations might also achieve greater power to find additional relationships involving large-scale spatial-memory-from-route experience by gathering a larger sample of behavioral data from each participant in the spatial-memory task. Additional spatial tasks, such as pointing and distance estimation, would provide a more well-rounded assessment of the underlying spatial representation and less task-specific variability. For example, our map reconstruction task may have included biases associated with the response field (blank map of just the path; e.g., Hund & Plumert, 2005; Huttenlocher, Hedges, & Duncan, 1991; Schmidt, 2004). Also, it would be interesting to examine how the relationships studied here might change as spatial representations develop over repeated route exposures. Finally, Hegarty et al. (2006) demonstrated that environmental learning tasks that used videos and virtual reality loaded on a separate factor than tasks in which learning occurred via direct experience with an environment. Although learning from visual media is clearly an important spatial ability, most environmental learning occurs through direct experience with the real world. Studies requiring participants to walk through actual environments would provide greater ecological validity. They might also address the possibility that the observed relationship between spatial and event memory resulted at least in part from similarities of format; both tests assessed memory for videos. However, if this were the case, it is unclear why order memory would mediate this relationship, as shown above. Also, other tasks in our cognitive battery (e.g., working memory tasks) shared the same general format (see things on a computer monitor and remember them) but failed to uniquely predict spatial memory. Finally, we ran an additional analysis including event recognition memory. Participants saw still pictures taken from the event movies, or similar lure movies, and made old or new judgments. Recognition data were not included above primarily because performance across the three movies (breakfast, party, and planters) showed poor internal reliability (α = .47). However, when a general event memory factor was created using event recall memory, event order memory, and event recognition, and the regression in Table 4 was run with this factor in place of event recall memory, this general event memory factor uniquely accounted for 5% of variance in DI.[6] This argues against the possibility that the relationship between event and spatial memory was specific to details of the tasks, and suggests that this relationship reflects individual differences in the ability to remember spatial and temporal structure. However, we cannot rule out the alternative possibility that what is shared between the two tasks is specific to watching movies and thus might not generalize to real-world event comprehension; it would be valuable to explore this in future studies.

Novel contributions of the current study are that it examined, in a continuous adult life span sample, contributors to spatial memory in the context of a large and well-measured set of general cognitive factors, several of which (event memory and event segmentation) are relatively unexplored in the spatial literature. In addition, a new method for assessing chunking in spatial memory was developed. We believe the modified bidimensional regression introduced here has substantial potential in future spatial memory research.

Conclusion

When people learn about a space, they learn from experiences in that space. In this study, the fact that memory for structured human activity uniquely predicts spatial-memory-from-route experience illustrates the importance of this. Accounting for the temporal structure of people's experience while learning the layout of novel spaces may prove crucial for explaining how they remember those spaces later.

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[6] It should be noted that reliability was also poor across the three different event memory measures (α = .51).

Appendix

Modification of bidimensional regression to include chunking

The following assumes familiarity with traditional bidimensional regression, which is described elsewhere (Friedman & Kohler, 2003; Tobler, 1965). We first describe model M_0, referred to in the Methods section, which does not include a chunking factor and is the traditional bidimensional regression approach to assessing the fit between two, 2-D sets of points (maps) using Euclidean transformations. Suppose there are n memorized landmarks or objects, and that (u_i, v_i) are the coordinates in memory, and that (x_i, y_i) are the actual coordinates. Nakaya (1997) defined the Euclidean transformation as

$$\begin{pmatrix} u_i \\ v_i \end{pmatrix} = \begin{pmatrix} \alpha_1 \\ \alpha_2 \end{pmatrix} + s\begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} x_i \\ y_i \end{pmatrix} + \begin{pmatrix} \epsilon_i \\ \eta_i \end{pmatrix}, \quad i = 1, \ldots n,$$

where ϵ_i and η_i are independent random errors assumed with common variance. A reparameterization of this gives us

$$\begin{pmatrix} u_i \\ v_i \end{pmatrix} = \begin{pmatrix} \alpha_1 \\ \alpha_2 \end{pmatrix} + \begin{pmatrix} \beta_1 & -\beta_2 \\ \beta_2 & \beta_1 \end{pmatrix}\begin{pmatrix} x_i \\ y_i \end{pmatrix} + \begin{pmatrix} \epsilon_i \\ \eta_i \end{pmatrix}, \quad i = 1, \ldots, n\,.$$

This (M_0) can be written as a multiple linear regression.

$$\begin{pmatrix} u_1 \\ \vdots \\ u_n \\ v_1 \\ \vdots \\ v_n \end{pmatrix} = \begin{pmatrix} 1 & 0 & x_1 & -y_1 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & 1 & x_n & -y_n \\ 0 & 0 & y_1 & x_1 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 1 & y_n & x_n \end{pmatrix}\begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \beta_1 \\ \beta_2 \end{pmatrix} + \begin{pmatrix} \epsilon_1 \\ \vdots \\ \epsilon_n \\ \eta_1 \\ \vdots \\ \eta_n \end{pmatrix}$$

To include the binary chunking variable (create M_1), we assume that each chunk has its own transformation model. Suppose that there are n_i objects in the ith chunk, i = 1, 2. Denote (u_{ij}, v_{ij}) and (x_{ij}, y_{ij}) as the memorized and actual position of the jth object in the ith chunk, respectively, j = 1,…,n_i. And let $(\alpha_{i1}, \alpha_{i2}, \beta_{i1}, \beta_{i2})$ be the transformation parameters for the ith chunk. Then we have for Chunk 1

$$\begin{pmatrix} u_{11} \\ \vdots \\ u_{1n1} \\ v_{11} \\ \vdots \\ v_{1n1} \end{pmatrix} = \begin{pmatrix} 1 & 0 & x_{11} & -y_{11} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & x_{1n1} & -y_{1n1} \\ 0 & 1 & y_{11} & x_{11} \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 1 & y_{1n1} & x_{1n1} \end{pmatrix}\begin{pmatrix} \alpha_{11} \\ \alpha_{12} \\ \beta_{11} \\ \beta_{12} \end{pmatrix} + \begin{pmatrix} \epsilon_{11} \\ \vdots \\ \epsilon_{1n1} \\ \eta_{11} \\ \vdots \\ \eta_{1n1} \end{pmatrix}$$

And for Chunk 2

$$\begin{pmatrix} u_{21} \\ \vdots \\ u_{2n_2} \\ v_{21} \\ \vdots \\ v_{2n_2} \end{pmatrix} = \begin{pmatrix} 1 & 0 & x_{21} & -y_{21} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & x_{2n_2} & -y_{2n_2} \\ 0 & 1 & y_{21} & x_{21} \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 1 & y_{2n_2} & x_{2n_2} \end{pmatrix} \begin{pmatrix} \alpha_{21} \\ \alpha_{22} \\ \beta_{21} \\ \beta_{22} \end{pmatrix} + \begin{pmatrix} \epsilon_{21} \\ \vdots \\ \epsilon_{2n_2} \\ \eta_{21} \\ \vdots \\ n_{2n_2} \end{pmatrix}$$

We can combine the above two models into one linear model by introducing an indicator variable. Let z_i = 0 if the ith object is in Chunk 1 and z_i = 1 if the ith object is in Chunk 2. Then we can modify M_0 as follows to get M_1:

$$\begin{pmatrix} u_1 \\ \vdots \\ u_n \\ v_1 \\ \vdots \\ v_n \end{pmatrix} = \begin{pmatrix} 1 & 0 & x_1 & -y_1 & z_1 & 0 & x_1z_1 & -y_1z_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & x_n & -y_n & z_n & 0 & x_nz_n & -y_nz_n \\ 0 & 1 & y_1 & x_1 & 0 & z_1 & y_1z_1 & x_1z_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 1 & y_n & x_n & 0 & z_n & y_nz_n & x_nz_n \end{pmatrix} \begin{pmatrix} \alpha_{11} \\ \alpha_{12} \\ \beta_{11} \\ \beta_{12} \\ \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \end{pmatrix} + \begin{pmatrix} \epsilon_1 \\ \vdots \\ \epsilon_n \\ \eta_1 \\ \vdots \\ \eta_n \end{pmatrix}$$

where $\delta_1 = \alpha_{21} - \alpha_{11}$, $\delta_2 = \alpha_{22} - \alpha_{12}$, $\delta_3 = \beta_{21} - \beta_{11}$, and $\delta_4 = \beta_{22} - \beta_{12}$. Testing the chunking effect is then equivalent to testing H_0 (no chunking): $\delta_1 = \delta_2 = \delta_3 = \delta_4 = 0$.

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