Psychological Research
DOI 10.1007/s00426-012-0452-x

ORIGINAL ARTICLE

Integrating spatial information across experiences

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Received: 6 April 2011 / Accepted: 18 August 2012

Abstract The current study examined the potential influence of existing spatial knowledge on the coding of new spatial information. In the Main experiment, participants learned the locations of five objects before completing a perspective-taking task. Subsequently, they studied the same five objects and five additional objects from a new location before completing a second perspective-taking task. Task performance following the first learning phase was best from perspectives aligned with the learning view. However, following the second learning phase, performance was best from the perspective aligned with the second view. A supplementary manipulation increased the salience of the initial view through environmental structure as well as the number of objects present. Results indicated that the initial learning view was preferred throughout the experiment. The role of assimilation and accommodation mechanisms in spatial memory, and the conditions under which they occur, are discussed.

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Integrating spatial information across experiences

The acquisition of spatial knowledge about important locations in our surroundings frequently does not occur during a single experience. Rather, as we revisit places we encounter and learn about new spatial features and relations within the environment. To date, very few studies have explicitly examined spatial memory organization when spatial relations are learned across multiple experiences with an environment. In particular, it is yet unclear what, if any, influence a previously established memory has on the coding and organization of new information. Likewise, it remains uncertain what influence new experiences may have on previously established memories, particularly when novel spatial information is subsequently encountered.

The current study was designed to evaluate the development and organization of spatial memory when novel spatial information is encountered across multiple experiences. Although research in this area has been rather limited, a review of existing literature that has examined the influence of either new experiences or new spatial information on memory serves to provide the basis for three classes of hypotheses about how memory might develop under such circumstances. Below, we outline these three possibilities.

Integration mechanisms in spatial memory

Accommodating new spatial information

Several lines of research have previously examined the organization of spatial knowledge structures following multiple, discrete experiences with a single set of spatial

Published online: 01 September 2012

relations (Kelly & Avraamides, 2011; Kelly & McNamara, 2010; Mou, Zhao, & McNamara, 2007; Shelton & McNamara, 1997, 2001; Valiquette, McNamara, & Labrecque, 2007; Yamamoto & Shelton, 2005). For example, Shelton and McNamara (2001) asked participants to study an array of objects from multiple viewing perspectives. Following learning, participants' memory for the array was evaluated by asking them to make *judgments of relative direction* (JRD) between object triplets (e.g., "Imagine standing at X facing Y. Point to Z."). In some cases, the researchers observed that participants were most accurate on judgments when the imagined heading (i.e., the direction from X to Y) during test was aligned with the initially experienced view, and demonstrated a decrease in performance as imagined headings became increasingly distant from this view (Experiment 7). However, when salient environmental geometry was aligned with one of the experienced views, the researchers observed that best performance occurred for judgments aligned with this structure, regardless of whether it coincided with the first or subsequently experienced view (Experiments 1 and 3).

Shelton and McNamara (2001) concluded that their participants interpreted the spatial relations of the array using the most salient experience encountered during learning, and relied on this experience to establish a coordinate system (or *spatial reference frame*) in memory for representing interobject relations. Participants' interpretation of the array established a *preferred direction* in memory from which retrieval of spatial information was facilitated. Judgments from imagined headings misaligned with this view produced longer and comparatively inaccurate responses, presumably because they required a computational process in order to infer spatial relations. The authors speculated that in some cases participants' initial experience with the array fostered an egocentric interpretation of the spatial structure based on the first learning view (e.g., *egocentric reference frame)*. In other instances, however, the salience of the spatial structure of the array aligned with a subsequent view initiated a reinterpretation of the array based on the new experience, and the establishment of a new preferred direction in memory (i.e., accommodation). Using a similar procedure, but also testing participants' memory between learning experiences, Valiquette et al. (2007) observed that an initially experienced view that was misaligned with salient array structure may be coded in memory, but could be replaced in favor of an aligned view after it is experienced. Such a preference for salient environmental structure is consistent with the findings of Mou and colleagues who have suggested that views aligned with the salient intrinsic structure of a configuration (e.g., rows and columns) may be generally preferred over misaligned views. Indeed, under some circumstances the salience of such structure has been shown to support the establishment of a preferred direction in memory even when an aligned view is never experienced (e.g., Mou et al. 2008, 2007; Mou & McNamara, 2002). In such cases, participants are considered to have relied on a structural interpretation of the interobject relations (e.g., *intrinsic reference frame*). Together, such studies suggest that spatial memory may be dynamic, recoding previously acquired information in light of new experiences. This may be especially true in cases where subsequent (but not initial) views are aligned with salient environmental structure.

Assimilating new spatial information

In contrast to research supporting an accommodation process in spatial memory, a recent study by Kelly and Avraamides (2011) found that spatial information acquired across multiple experiences might be strongly influenced by a previously established reference frame. In Experiment 1, participants first saw two objects from two adjacent views separated by 45°. Importantly, either the first or second visual experience was aligned with salient environmental structure (stripes on the table). Following this visual exposure, participants remained at the second viewing location and were blindfolded as seven new objects were added to the array. Participants then explored the entire object array haptically. Subsequent judgments of relative direction limited to the seven haptically learned objects was found to be best for the heading corresponding to the visual experience aligned with salient environmental cues, regardless of whether it was presented first or second, and thus whether it was aligned or misaligned with the haptic learning experience. It is worth noting that performance was also relatively improved for the heading aligned with the haptic study view suggesting that the second experience may also have influenced participants' memory, albeit to a lesser extent. In Experiment 2, the initial visual experience did not include any array objects, but rather allowed participants to view the striped table from a single learning perspective. All nine array objects were subsequently studied haptically from a location aligned or misaligned with the visual learning experience. Again, the initial visual experience, here limited to environmental cues (stripes), influenced the reference frame adopted to represent the haptically learned objects. The authors concluded that participants established a reference frame in memory during the visual learning experience and subsequently integrated new haptically acquired spatial information into this existing memory, and that this form of assimilation did not require the presence of information common to visual and haptic experiences (i.e., the two objects present during visual learning in Experiment 1).

Similar results have been provided by Kelly and McNamara (2010) who asked participants to study and learn two embedded arrays under several conditions before making judgments of relative direction within each array. In one experiment, the authors observed that when participants' initial study view was aligned with salient environmental structure of one array, judgments within the second array were facilitated along that heading, even when the second view was misaligned by 135° from the initial view (Experiment 1).

Interestingly, the authors also observed that an initially established memory could be reorganized under some circumstances. In another experiment, participants were asked to study both arrays before studying only one of the arrays from a new location (Experiment 3). Importantly, the second view was aligned with the geometry of the remaining array. The authors observed that judgments made within each array demonstrated facilitation at the imagined heading aligned with the structure of the array present during the second viewing (a pattern of performance more consistent with accommodation). However, this facilitation only occurred after participants were required to point to the object locations for both arrays while standing at the second view. It is possible that the recoding effect observed in this experiment was attributable to post-encoding processes initiated by task demand (i.e., egocentric pointing from the second viewing location), and do not necessarily reflect a default processing mode (cf. Meilinger, Berthoz, & Wiener, 2011). Regardless, the results of Experiment 1 provide a clear indication that assimilation mechanisms can play a strong role during encoding.

Specifying relations between multiple reference frames

Greenauer and Waller (2010; Experiment 3) have provided some evidence suggesting that the organization of an integrated memory (i.e. the representation of spatial relations acquired during discrete experiences) developed over sequential viewing experiences may be relatively uninfluenced by previously established knowledge structures. In one experiment, the authors asked participants to study two semantically and spatially distinct arrays of objects from a single learning perspective. The salient intrinsic structure of each array was offset by 90° from each other, and by 45° from the centrally located learning view. Participants were required to learn one array prior to being shown both arrays simultaneously. Importantly, the perceptually salient axis between the arrays was aligned with the learning view. The authors observed that judgments of relative direction made between the arrays were facilitated at the imagined heading aligned with the learning view, which was also aligned with the perceptually salient structure created when the two arrays were viewed simultaneously. Judgments made on objects within each array, however, demonstrated facilitation from the imagined heading aligned with the structure intrinsic to that set of objects. This result was similar to those observed in other experiments in which both arrays were learned simultaneously during the learning phase (e.g., Experiment 2). The authors concluded that participants had established and maintained a relatively stable memory for the initially learned array during the first viewing that was aligned with the salient within-array structure, but had established in memory a second reference frame aligned with the between-array structure in order to relate spatial information between the two configurations (i.e. a macroreference frame). Thus, while participants were able to integrate spatial information between the arrays, there was no evidence that the representation of the initially learned configuration of objects influenced the integration process. Indeed, to the extent that within- and between-array judgments demonstrated distinct preferred directions, the authors speculated that within-array reference frames can exist separately from each other but still be organized into a comprehensive knowledge structure, which is itself structured relatively independently of the parts that comprise it.

The flexibility of integration mechanisms in spatial memory

A recent study by Meilinger, Berthoz, and Wiener (2011) supports the notion that integration mechanisms in spatial memory may be quite flexible, taking one of several forms depending on circumstances. In this study, participants sequentially learned two sets of location triplets before being asked to travel between all six locations following the shortest route possible. Importantly, participants learned each location triplet either from the same or different viewing locations. In order to travel efficiently between all six locations participants needed to integrate the spatial information acquired during each learning experience. The authors observed that fewer errors were made when location triplets were learned from the same, compared to different, viewing location suggesting a cost associated with integrating spatial information acquired from different views. Interestingly, when movement during test was initiated from the second viewing location error rates for locations learned from the first viewing location were comparatively higher (Experiment 1). Under circumstances where two views were experienced but movement was initiated only after returning to the initial viewing location, error rates were higher for location triplets learned from the second viewing location (Experiment 2). The authors interpreted the findings as indicating (a) that integration occurred only when required to produce a response rather than during encoding and (b) that either previously acquired or novel information could serve as the basis for the integration processes, depending on circumstances.

In the context of the current study, the findings of Meilinger et al. (2011) further suggest the possibility that both assimilation and accommodation mechanisms may support spatial memory organization. Furthermore, the observation of an integration cost may indicate that, at least initially, discrete representations for sets of locations may have been established prior to integration. In conjunction with the previously reviewed findings these results suggests a flexible and adaptive system for integrating spatial information. However, the organization of spatial memory following integration remains unclear. Specifically, it is yet unknown what, if any, influence integration has on the organization of spatial knowledge, either in part (i.e., on previously encoded versus newly acquired information) or wholly, and how knowledge structures may change over time and experience.

Although the reviewed studies support the possibility of several strategies for organizing spatial information acquired across discrete experiences, it is important to note that each of these studies was designed to address a comparatively narrow theoretical question. Consequently, conclusions based on these studies are necessarily limited by design idiosyncrasies. For example, judgments of relative direction in Kelly and Avraamides (2011) were limited to the new objects while those in Kelly and McNamara (2010) were exclusively made within each set (or array) of objects. Thus, while these studies clearly demonstrate an across-experience effect, they are unable to address what influence multiple experiences have on the organization of an *integrated* spatial memory. Conversely, although Greenauer and Waller (2010) explicitly evaluated between-array judgments, the distinction between learning experiences in this study was comparatively limited inasmuch as participants remained at a single viewing location throughout learning. Even with the addition of a second array, the stability of this view may have made it a particularly salient orientation for integrating spatial information; in effect encouraging participants to treat the two phases as a single, extended learning session rather than distinct viewing sessions. In light of these differences, it remains unclear what processes support the integration of discrete sets of spatial relations across experiences and how spatial relations are organized in memory.

In the current study, we evaluated the organization of spatial memory when a new view (e.g., Mou et al., 2007; Shelton & McNamara, 2001) is associated with novel spatial information (e.g., Greenauer & Waller, 2010; Kelly & McNamara, 2010) within the visual modality (cf. Kelly & Avraamides, 2011). To the extent that the current study focused on observing possible changes to memory over the course of learning, it was important to establish an experimental context that could support such processes. To this end, based on Shelton and McNamara's (2001) observation that subsequent views aligned with array structure may facilitate a change in memory organization, the most salient environmental structure was presented at the second view. In addition, to the extent that Kelly and Avraamides (2011) have demonstrated that an initial view (i.e., memory) can influence the subsequent encoding of novel relations, we added new information during the second exposure. This enabled us to explicitly evaluate how the relations among new objects are represented, as well as how this information was related to previously learned object locations. Importantly, unlike previous studies, we probed participants' memory following each of the two viewing experiences (e.g., Valiquette et al., 2007) and for unique sets of object relations (e.g., Greenauer & Waller, 2010). Specifically, we examined the organization of participants' memory for: (1) five initially learned objects following the first learning session (Pre-Old Judgments); (2) the same five objects following the second learning session from a novel view (Post-Old Judgments); (3) five new objects presented during the second learning session (New Judgments); (4) the relations between objects introduced during different phases (Between Judgments).

Central to distinguishing possible differences in memory either across learning sessions or between judgment types was determining from which imagined heading participants were fastest and most accurate to respond (i.e., preferred heading) during the test phase. To this end, when an effect of heading was observed, participants' preferred heading was initially evaluated by comparing performance at the two experienced views (0° and 315° imagined heading). When performance at one of the headings was clearly observed to be superior, planned contrasts were fit to the data in order to further evaluate the form of participants' memory. However, inasmuch as differences between adjacent imagined headings may be small, and statistically non-significant, such differences can still be meaningful in interpreting the data. Thus, in addition to pairwise comparisons, participants' patterns of performance across all eight headings were evaluated using trend analyses (*predicted pattern analysis*; Levin & Newmann, 1999) in order to infer which of the two headings was likely preferred. Finally, in order to directly compare memory organization between judgment types we computed interaction contrasts based on the difference between the predicted performance of the 0° and 315° contrasts at each heading.

Main experiment

Methods

Participants

Eighteen undergraduate students from the University of Cyprus participated in this experiment for course credit in their introductory psychology course or a small financial compensation (€10).

Materials and stimuli

Three-dimensional virtual models were used for learning and testing stimuli. The learning model depicted five or 10 objects (depending on phase, see below; the objects used were pliers, jeep, tree, basket, roller skate, grater, starfish, flask, chessboard, lantern, and basket) arranged on the floor and centered in a circular chamber with a diameter of 7 m (see Fig. 1). The learning model was scaled such that the distance between participants and the closest object was 1.29 m, and the shortest distance between objects was .91 m. For each participant, each learning object was randomly assigned to one of the 10 locations depicted in Fig. 2. The testing model depicted a textured ground plane and horizon (i.e., a grassy field and sky). Test stimuli were presented as Greek text overlaid on the testing model.

A learning and a testing station were established at opposite ends of a large (10 × 4.3 m) laboratory room. A script written in the Python language controlled the presentation of the virtual environment and test items. Stimuli were presented to participants in an nVisor SX (NVIS; Reston, VA, USA) head-mounted display (HMD) with a resolution of 1,280 × 1,024 and 60° diagonal field of view. An Intersense (Billerica, MA, USA) InertiaCube3 inertial tracker providing online (180 Hz) directional data with 1° root-mean-square error was affixed to the top of the HMD and used to track participants' facing direction and to update participants' viewpoint in the HMD. In addition, these data were used to measure response direction for test items; responses were effected by participants turning their head (and body if needed) to face a target direction and pressing a button on a hand-held mouse. Participants' final head orientation was recorded and used to compute the angular error of the response. In addition, response latency was also recorded (measured from the onset of the test stimulus to the final button press).

Each test item (i.e., judgment of relative direction or JRD) was presented in two parts. First, an orienting stimulus (e.g., "Imagine standing at X facing Y.") was presented to establish an imagined heading. Second, following a button press, a target stimulus (e.g., "Point to Z") indicated the target toward which participants should turn to face. Three sets of 48 test items, reflecting distinct *Judgment Types*, were created (for a total of 144 unique trials) by selecting three object locations in the array (the object assigned to each location was random for each participant). Each set of 48 trials was composed of six trials at each of eight imagined headings (from 0 to 315°, in 45° increments). Each location was used approximately an equal

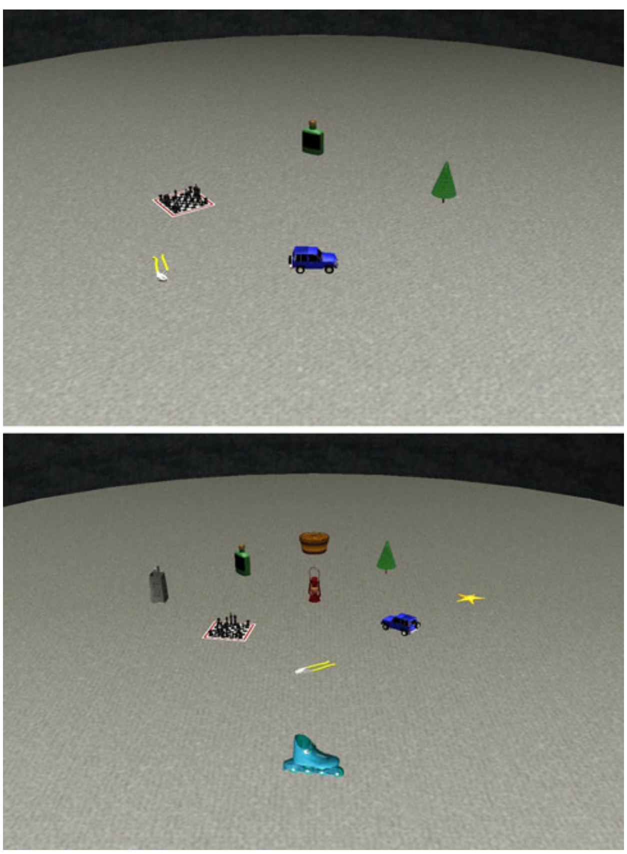

Fig. 1 Screenshot of a sample learning stimulus presented to participants during the first (*top panel*) and second (*bottom panel*) learning phase in the Main experiment

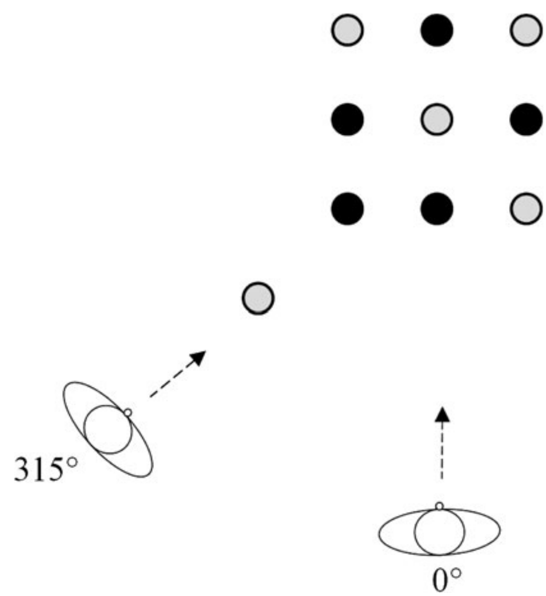

Fig. 2 Plan view of the learning phases of Main experiment. Participants viewed an array of five objects (*black circles*) from 0° during the first learning phase. During the second learning phase, participants viewed the original five objects as well as five new objects (*gray circles*) from 315°

number of times for each component of the trial lists, with the constraint that target locations were approximately equally distributed around the participant within the six trials at each imagined heading. One set of test items (used for Pre-Old and Post-Old judgments in the analyses below) included only the five locations presented during the initial learning phase in each component of the JRD. One set (New) included only the five new locations presented during the second learning phase. Finally, one set of test items (Between) was constructed by using one old and one new location in the orienting stimulus component (e.g., "At OLD/NEW, Facing NEW/OLD"); target stimuli for these items were approximately equally represented by old and new locations.

Procedure

Prior to beginning the experiment, the basic procedure was described to participants. Following this introduction, participants were familiarized with the HMD as well as with how to respond to test questions by completing several training trials based on a small practice array. The accuracy and speed of responses were both emphasized during the practice session. After participants demonstrated that they understood the procedure and task, the experimental session began. The experimental procedure consisted of an initial learning phase, an initial testing phase (Pre-Old judgments), a second learning phase, and a second testing phase (Post-Old, New, and Between judgments).

Initial learning phase

Participants donned the HMD and were introduced to the five objects that comprised the initial learning array. The virtual object and name (in Greek text) of each object were presented one at a time, in random order, against a uniform gray background. Participants used the handheld mouse to indicate they were familiar with the displayed stimulus and were ready to view the next one. After all five objects had been introduced, participants were provided an opportunity to look around the virtual chamber (without the objects) before being instructed to center their view on a fixation stimulus, thus ensuring that all objects would appear in participants' line of sight at the beginning of learning. When participants indicated that they were ready to begin, the experimenter initiated the learning phase; the fixation stimulus was removed and the five to-be-remembered objects appeared on the floor. This initial viewing orientation was arbitrarily labeled 0°.

The objects remained visible to participants for 30 s. After this interval, the objects were removed and a small dot was displayed in the center of the HMD (and yoked to participants' facing direction). The name of one object also appeared at the top of the display. Participants were instructed to look at (i.e., place the dot over) the remembered location of the named object. The experimenter monitored participants' responses on a desktop monitor that displayed participants' view and, using the keyboard, entered whether or not participants' indicated an approximately correct location. This procedure was repeated for each object in the learning array (the order of presentation was randomized following each display of objects). Participants then repeated this study-test procedure until they were able to accurately point to each object as determined visually by the experimenter. When the experimenter determined that participants had learned the array sufficiently to complete the test trials (generally no more than two viewings), participants removed the HMD and were taken to the testing station.

Initial testing phase

Participants again donned an HMD and were reminded to try to be as accurate in their responses as possible and to answer each test item as quickly as possible. When participants were ready, they initiated the testing program by pressing a hand-held mouse button. Participants then completed the 48 Pre-Old judgments of relative direction. The order of presentation was randomized for each participant.

Second learning phase

Participants returned to the learning station. In order to reinforce that they were about to experience a new view of the virtual environment, they were guided several steps left and slightly rotated relative to their initial learning position, a shift consistent with the to-be-experienced view in the virtual model. Participants donned the HMD and followed the learning procedure previously described with the following exceptions. First, the view depicted in the HMD was 45° to the left of the initial learning location relative to the center of the array (arbitrarily labeled 315°). Second, five additional objects were added to the array, increasing the total number of objects to 10. As in the previous learning phase, the objects and names of these five new objects were introduced to the participants prior to viewing the virtual chamber and array.

Second testing phase

The second testing phase followed the testing procedure previously described with the exception that participants completed 144 test trials (48 Post-Old, 48 New, and 48 Between judgments). The 144 trials were randomly presented to each participant.

Design and analyses

Univariate analyses of variance were used to evaluate participants' pointing accuracy and latency. Pointing accuracy was defined as the absolute difference between the actual and estimated target direction. Latency was measured from the onset of the orienting stimulus until participants rotated 10°. Although experimental trials were designed and presented to participants in such a way as to separate orientation latency from response latency (e.g., participants were instructed to imagine a given heading during the orienting phase of each test trial prior to initiating target presentation), we are unable to verify that participants consistently followed experimental instructions. Consequently, it was deemed most appropriate to combine orientation and response components even if this meant including additional variance in our analyses.

When an effect of heading was observed, participants' preferred heading was initially evaluated by comparing performance at the 0° and 315° imagined headings. When performance at one of the headings was clearly observed to be superior, planned contrasts were fit to the data in order to further evaluate the form of participants' memory. In cases where pairwise comparisons between adjacent headings did not indicate a significant difference in performance, participants' preferred heading was inferred using trend analyses (*predicted pattern analysis*; Levin & Newmann, 1999). This procedure allowed us to fit planned contrasts representing expected, prototypical patterns of performance that have been used previously to identify spatial reference frames in memory (e.g., Greenauer & Waller, 2008; for a detailed discussions of contrasts, see Keppel & Wickens, 2004, and Rosenthal & Rosnow, 1985). The use of this procedure reduced the number of statistical tests that needed to be conducted, and thus minimized the potential for erroneous conclusions based on a large number of pairwise comparisons. Contrast weights (−0.75, 0.25, 1.25, 0.25, 1.25, 0.25, −0.75, −1.75) were selected using the procedure described by Levin and Neumann (1999), and were the same as those employed by Greenauer and Waller (2008). These weights represent a quadratic pattern of performance demonstrating superior performance at one of the eight headings, a linear decrease in performance as imagined headings deviate from this preferred orientation, and facilitation at the counter-aligned heading (facilitation at a counter-aligned heading is frequently observed in studies on spatial reference frames: e.g., Greenauer & Waller, 2008; Roskos-Ewoldsen et al. 1998; Hintzman et al. 1981; Rieser, 1989; Shelton & McNamara, 2004; Waller et al. 2008). For each judgment type, the contrast was fit to the data twice: once with the minimum of the contrast corresponding to the initial learning view (0°) and once with the minimum corresponding to the second learning view (315°). Effect sizes were examined by evaluating the percent of variance associated with imagined heading accounted for and unaccounted for by each contrast (see Keppel & Wickens, 2004). Finally, possible changes in reference frames between judgment types were further evaluated by means of an interaction contrast that reflected the differences in the predicted performance of the 0° and 315° contrasts at each heading. Specifically, we fit this interaction contrast to the standardized difference at each heading for two judgments types. A significant fit of an interaction contrast was interpreted as indicating that the organization of participants' memory for the two sets of relations was different from each other.

Prior to analyses, outlying latencies and pointing errors (defined as > 3 SD of the mean) were trimmed, resulting in 2.76 % of trials being discarded. In addition, initial omnibus analyses indicated that assumptions of sphericity were violated in some cases. When appropriate, the Greenhouse-Geisser test statistic was used. Finally, for all analyses, determination of significance was based on $\alpha = .05$.

Results

Potential speed-accuracy tradeoffs were evaluated by correlating absolute pointing error and response latency within and between participants. Mean within-participant latency-error correlations did not significantly differ from zero, $t(17) = 1.27$, $p = .237$. Between participants, latency and error were significantly positively correlated, $r(18) = .586$, $p = .011$. Thus, no evidence of a speed-accuracy tradeoff was observed.

Performance at each heading as a function of judgment type is depicted in Figs. 3 and 4. In general, the results indicated that after the first learning session (Pre-Old judgments), participants demonstrated a clear preference for the imagined heading aligned with the learning view. However, following the second learning session with five additional objects, test questions requiring participants to integrate the two experiences (Between judgments) showed facilitation at the imagined heading aligned with the new view. Thus, the formation of a memory representation encompassing all 10 objects appears relatively uninfluenced by participants' original memory. These conclusions were supported by statistical analyses that evaluated the effect of heading for each judgment type.

A 4 (Judgment Type) × 8 (Imagined Heading) repeated measures analysis of variance was conducted on participants' pointing accuracy and latency. For pointing accuracy this analysis revealed a significant effect of Judgment Type, $F(3, 51) = 3.35$, $p = .026$, $\eta_p^2 = .165$. Pre-Old judgments ($M = 40.87$, $SD = 15.41$) were significantly

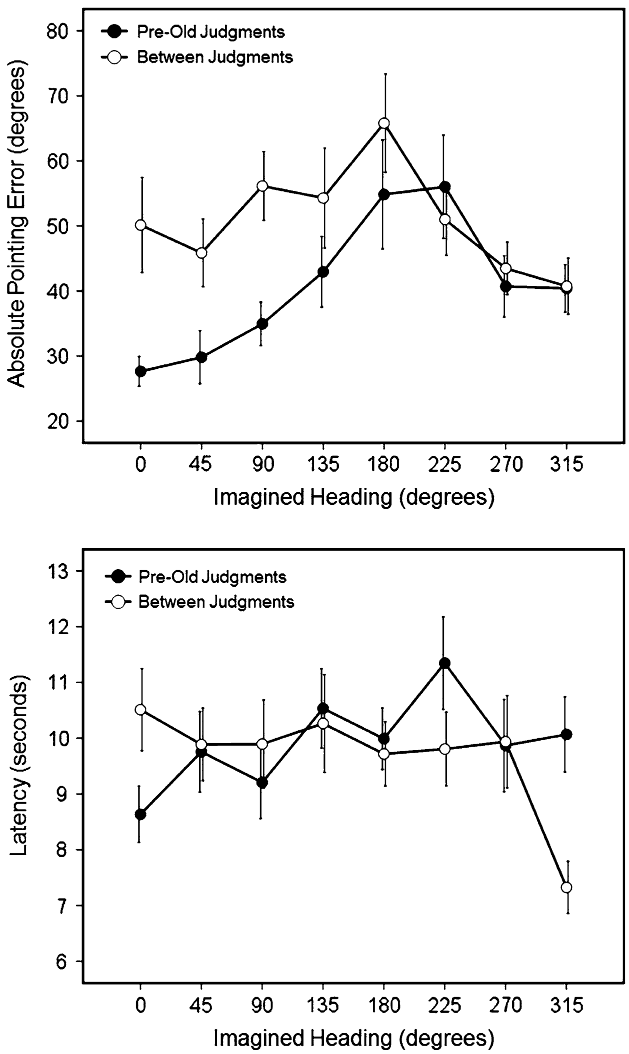

Fig. 3 Response accuracy and latency as a function of imagined heading for Pre-Old and between judgments in the Main experiment. *Error bars* represent standard errors

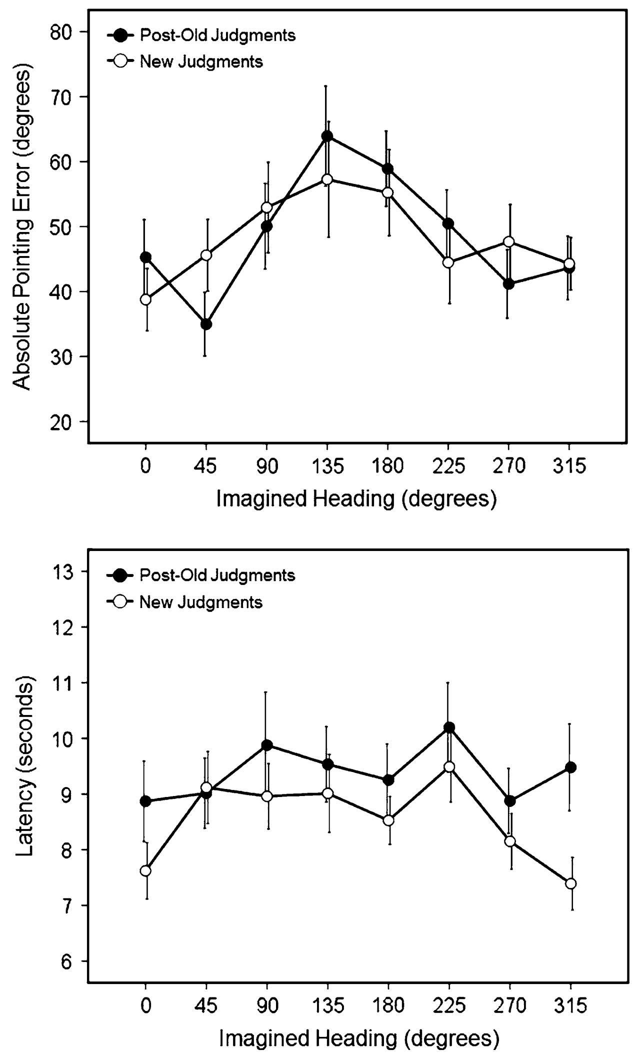

Fig. 4 Response accuracy and latency as a function of imagined heading for Post-Old and New judgments in the Main experiment. *Error bars* represent standard errors

more accurate than Between judgments ($M = 50.65$, SD = 13.74), $F(1, 17) = 14.36$, $p < .001$, $\eta_p^2 = .458$, but not significantly more accurate than Post-Old ($M = 48.29$, SD = 19.5) or New judgments ($M = 48.27$, SD = 18.09; $ps \geq .069$). The effect of imagined heading was also significant, $F(3, 52) = 6.83$, $p < .001$, $\eta_p^2 = .287$. A significant interaction between these factors was also observed, $F(21, 357) = 1.77$, $p = .020$, $\eta_p^2 = .094$.

For latency repeated measures analysis of variance also revealed a significant effect of Judgment Type, $F(2, 33) = 8.43$, $p < .001$, $\eta_p^2 = .331$. Pre-Old judgments ($M = 9.89$, SD = 2.46) were significantly slower than New judgments ($M = 8.52$, SD = 1.92), $F(1, 17)$ 2.07, $p < .001$, $\eta_p^2 = .468$, but did not differ from Post-Old ($M = 9.37$, SD = 2.59) or Between judgments ($M = 9.62$, SD = 2.56; $ps \geq .168$). A significant effect of imagined heading was also observed, $F(7, 119) = 6.47$, $p < .001$, $\eta_p^2 = .276$. The interaction between these factors was significant, $F(21, 357) = 2.99$, $p < .001$, $\eta_p^2 = .150$. Below, we evaluate performance for each judgment type separately before evaluating potential changes in the organization of participants' memory attributable to our procedure.

Pre-Old judgments

For pointing accuracy the effect of heading was significant, $F(3, 47) = 6.10$, $p = .002$, $\eta_p^2 = .264$. A planned comparison indicated that participants were significantly more accurate making judgments from the 0° ($M = 27.65$, SD = 9.75) than the 315° ($M = 40.40$, SD = 15.53) imagined heading, $t(17) = 3.43$, $p = .003$. The 0° contrast significantly described the data, $F(1, 17) = 11.37$, $p = .004$, accounting for 53.55 % of the variance associated with imagined heading and leaving a non-significant amount of variance unaccounted for ($p = .053$).[1] The 315° contrast did not significantly describe the data ($p = .116$).

For latency the effect of heading was also significant, $F(7, 119) = 4.17$, $p < .001$, $\eta_p^2 = .197$. A planned comparison indicated that participants were significantly faster make judgments from the 0° ($M = 8.63$, SD = 2.16) than the 315° ($M = 10.07$, SD = 2.87) imagined heading, $t(17) = 2.29$, $p = .035$. The 0° contrast significantly described the data, $F(1, 17) = 22.68$, $p < .001$, accounting for 61.96 % if the variance associated with imagined heading and leaving a non-significant amount of variance unaccounted for ($p = .109$). The 315° contrast did not significantly describe the data ($p = .685$).

Post-Old judgments

Analysis of pointing accuracy for the original 5 items following the second learning phase (Post-Old) revealed a significant effect of heading, $F(7, 119) = 6.07$, $p < .002$, $\eta_p^2 = .263$. A planned comparison indicated that accuracy at 0° and 315° did not significantly differ from each other ($p = .758$). The 0° contrast significantly described the data, $F(1, 17) = 15.77$, $p < .001$, accounting for 38.33 % of the variance associated with imagined heading, but left a significant amount of variance unaccounted for, $F(6, 119) = 4.37$, $p = .001$. Similarly, the 315° contrast also significantly described the data, $F(1, 17) = 12.17$, $p = .003$, accounting for 22.38 % of the variance associated with imagined heading and leaving a significant amount of variance unaccounted for, $F(6, 119) = 5.50$, $p < .001$. The interaction contrast comparing accuracy for Pre-Old and Post-Old performance was not significant, $p = .134$ (for latency, $p = .129$), indicating that participants' memory for the original five objects was not substantially influenced following the second learning phase. The effect of heading in latency was not significant ($p = .260$).

New judgments

Analysis of pointing accuracy for New judgments did not reveal a significant effect of heading ($p = .127$). The interaction contrast comparing New and Pre-Old judgments did not obtain significance, $F(1, 17) = 3.87$, $p = .066$, $\eta_p^2 = .186$. For latency, however, the effect of heading was significant, $F(7, 119) = 4.41$, $p < .001$, $\eta_p^2 = .206$. A planned comparison indicated that latency at 0° and 315° did not significantly differ from each other ($p = .510$). The 0° contrast significantly described the data, $F(1, 17) = 10.50$, $p = .005$, accounting for 49.20 % of the variance associated with imagined heading, but left a significant amount of variance unaccounted for, $F(6, 119) = 2.61$, $p = .028$. The 315° contrast also significantly described the data, $F(1, 17) = 16.32$, $p < .001$, accounting for 54.01 % of the variance associated with imagined heading, but left a significant amount of variance unaccounted for, $F(6, 119) = 2.37$, $p = .044$. However, the interaction contrast on latency was significant, $F(1, 17) = 5.54$, $p = .031$, $\eta_p^2 = .246$, indicating that New objects were coded using a different reference frame than that observed for Pre-Old judgments.

Between judgments

Analysis of pointing accuracy revealed a significant effect of heading, $F(7, 119) = 2.16$, $p = .043$, $\eta_p^2 = .113$. A planned comparison indicated that accuracy at 0° and 315° did not significantly differ from each other ($p = .298$). The 0° contrast did not significantly describe the data ($p = .345$). The 315° contrast, however, did significantly describe the data, $F(1, 17) = 9.67$, $p = .006$, accounting for 71.00 % of the variance associated with imagined heading and leaving a non-significant amount of variance unaccounted for ($p = .603$).

For latency the effect of heading was also significant, $F(7, 119) = 6.16$, $p < .001$, $\eta_p^2 = .266$. A planned comparison indicated that participants were significantly faster making judgments from the 315° ($M = 7.32$, SD = 1.98) than the 0° ($M = 10.51$, SD = 3.13) imagined heading, $t(17) = 5.53$, $p < .001$. The 0° contrast did not significantly describe the data ($p = .401$). However, the 315° contrast did significantly describe the data, $F(1, 17) = 17.64$, $p < .001$, accounting for 29.29 % of the variance associated with imagined heading, but left a significant amount of variance unaccounted for, $F(6, 119) = 5.08$, $p < .001$. The interaction contrasts comparing Pre-Old and Between judgments was significant for both pointing accuracy and latency, $F(1, 17) = 10.37$, $p = .005$, $\eta_p^2 = .379$ and $F(1, 17) = 19.423$, $p < .001$, $\eta_p^2 = .533$ respectively, indicating that the reference frame used for integration across experiences was different from that used during the initial learning experience.

Discussion

The current experiment was designed to evaluate the organization of spatial memory when novel spatial

[1] Depiction of this data suggested the possibility of a sawtooth pattern of performance that is indicative of an intrinsic reference frame (Mou & McNamara, 2002). An intrinsic contrast (contrast weights with a minimum at 0° = −1.625, 0.375, −0.625, 1.375, −0.625, 1.375, −0.625, 0.375; Greenauer and Waller 2008) was fit to this data and was found to describe the data well, $F(1, 17) = 5.79$, $p = .028$. However, although this contrast was able to account for 21.50 % of the variance associated with imagined heading, unlike the quadratic contrast it left a significant amount of variance unaccounted for, $F(6, 119) = 3.82$, $p = .003$.

information is encountered across multiple experiences. Unlike previous studies, we explicitly examined the organization of participants' memory after each learning experience, which allowed us to evaluate directly the formation of an integrated memory structure. In addition, we evaluated the memory organization for the entire configuration (i.e., Between judgments) as well as for specific subsets (i.e., Pre-Old, Post-Old, and New judgments) of spatial relations that were presented to participants at different times, allowing us to evaluate possible changes to memory over the course of learning. Our results are most consistent with the notion that existing knowledge structures may have only a limited influence on the encoding of new spatial information.

Specifically, our results showed that participants demonstrated a clear preference for the original learning view when tested immediately after this experience. This pattern of performance indicates that participants had organized their memory of the initial five objects based on a preferred reference direction aligned with the initial view of the array. However, following the second viewing session in which five additional objects were added and the entire array was viewed from a new location, the first experienced view was no longer dominant. Rather, when making judgments requiring the integration of the two subsets of objects, participants were faster and more accurate when adopting the imagined heading aligned with the new experience. This result suggests that participants had established a different preferred direction in memory aligned with the second view, around which they organized their memory for all ten objects.

It is worth noting, however, that judgments performed within each array following the second learning experience exhibited facilitation at both experienced perspectives. Although the integration of the two arrays into a unified representation was clearly influenced by the second experience, this did not completely overwrite the initial memory (cf. Kelly & McNamara, 2010; Shelton & McNamara, 2001); which may in fact have influenced the encoding of the novel array. This finding is at least partly consistent with those of Kelly & Avraamides (2011, Experiment 1) who observed facilitation for both the visual and haptic perspectives when they were misaligned. We discuss the implications of dual facilitation for a single preferred direction in memory within an integrated spatial representation in the "General discussion".

Supplementary experiment

It is important to make explicit that our results do not preclude the possibility that new experiences and information might be assimilated into existing spatial memories (e.g., Kelly & Avraamides, 2011; Kelly & McNamara, 2010; Shelton & McNamara, 2001). However, we speculate that a comparatively large amount of new information must be present before an individual is likely to disregard the potential utility of an existing knowledge structure when encoding new information. In short, the relative informational weight of each experience (e.g., number of object relations, alignment with environmental structure) may determine the direction in which integration occurs. The relatively richer spatial knowledge provided by an initial visual experience that is reinforced by a salient environmental axis, compared to learning experiences that do not offer these advantages, could promote assimilation. Similarly, the results of the previous experiment notwithstanding, we suspected that new spatial information could be readily assimilated into an existing knowledge structure when a comparatively small amount of additional information needs to be remembered, provided the existing memory offered a sufficiently salient and flexible framework for integrating new information (e.g., Shelton & McNamara, 2001). A supplemental experiment examined this possibility.

Nineteen students participated in a modified version of the previous experiment in which they were required to learn the locations of seven objects from 0° during the first learning phase before studying all ten objects from a new viewing location (315°, see Fig. 5). The configuration of the initial seven objects provided a salient environmental structure (i.e., rows and columns) aligned with the first

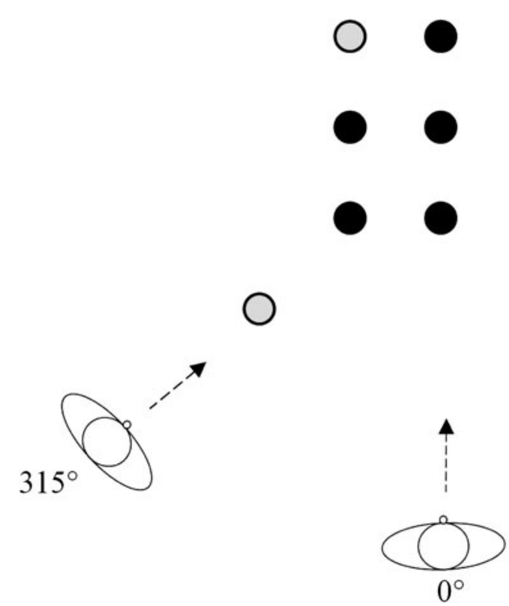

Fig. 5 Plan view of the learning phases of Supplementary Manipulation. Participants viewed an array of seven objects (*black circles*) from 0° during the first learning phase. During the second learning phase, participants viewed the original seven objects as well as three new objects (*gray circles*) from 315°

learning view. In this way, we attempted to provide participants with a coherent, salient, and unifying framework that could be easily used to assimilate the relatively small amount of new information encountered during the second learning experience. As in the Main experiment, participants' memory was tested after each learning phase. However, because the limited number of new objects presented during the second viewing was insufficient to create test trials at all imagined headings, no New judgments were presented during testing.

Performance at each heading as a function of judgment type is depicted in Figs. 6 and 7. Trend analyses on these data were less clear due to the multiple patterns in the data (i.e., the presence of both quadratic and sawtooth patterns); for brevity we report only the relevant pairwise comparisons. Analyses of participants' pointing accuracy revealed a significant effect of heading, $F(4, 75) = 3.91$, $p = .005$, $\eta_p^2 = .179$, but no effect of Judgment Type ($p = .440$) and no interaction between these factors ($p = .250$). Similarly, latency analyses indicated a significant effect of heading, $F(2, 41) = 3.12$, $p = .048$, $\eta_p^2 = .148$, but no effect of Judgment Type ($p = .056$) and no interaction ($p = .070$). Collapsing across Judgment Type, pointing accuracy was significantly better at 0° ($M = 25.88$, SD = 15.49) than 315° ($M = 35.10$, SD = 16.14), $t(18) = 5.03$, $p < .001$. Similarly, latencies at 0° ($M = 8.75$, SD = 2.80) were significantly faster than at 315° ($M = 9.45$, SD = 2.51), $t(18) = 2.39$, $p = .028$. Although some omnibus factors were not significant, within-judgment comparisons of heading were considered appropriate in light of the specific hypotheses being examined. These analyses revealed that pointing accuracy was significantly better at 0°

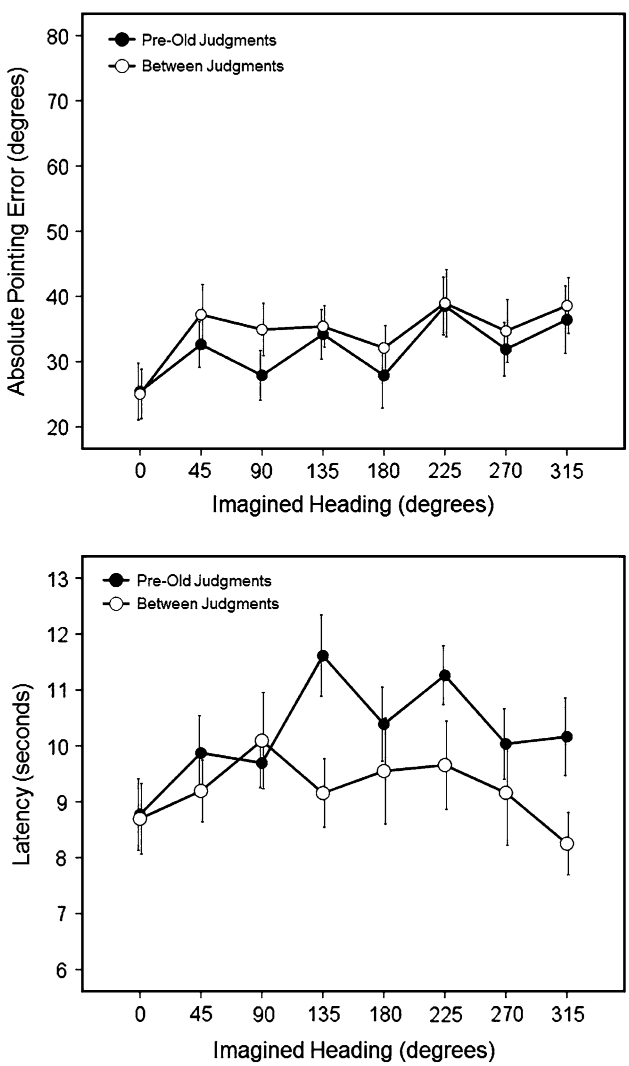

Fig. 6 Response accuracy and latency as a function of imagined heading for Pre-Old and Between judgments in the Supplementary Manipulation. *Error bars* represent standard errors

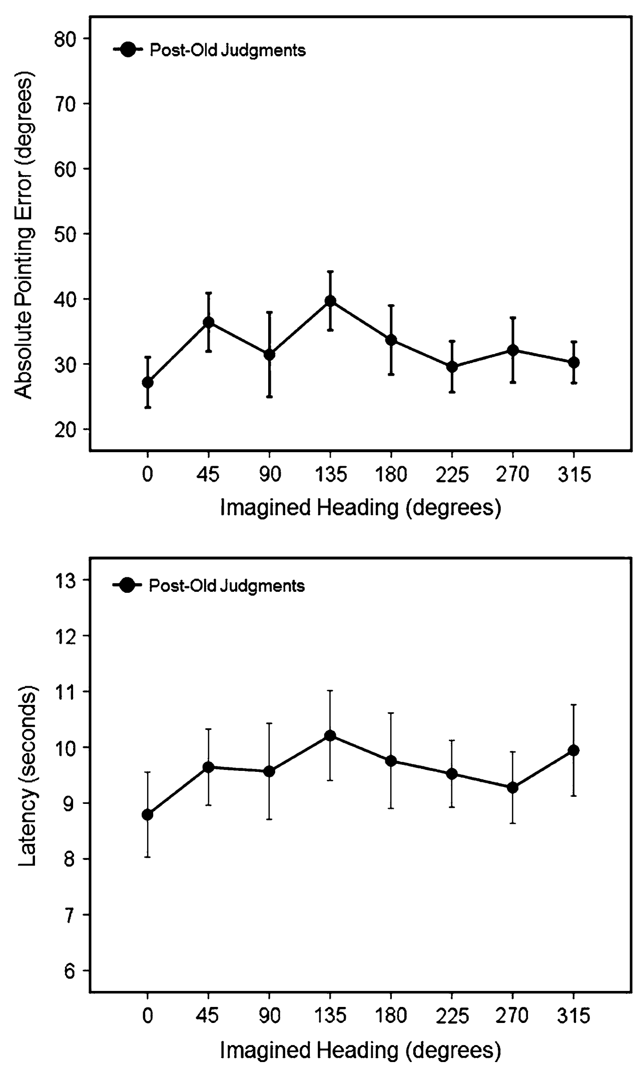

Fig. 7 Response accuracy and latency as a function of imagined heading for Post-Old judgments in the Supplementary Manipulation. *Error bars* represent standard errors

($M = 25.42$, SD $= 18.96$) than 315° ($M = 36.44$, SD $= 22.63$) for Pre-Old judgments, $t(18) = 3.00$, $p = .008$. Similarly, pointing accuracy was significantly better at 0° ($M = 25.05$, SD $= 16.62$) than 315° ($M = 38.59$, SD $= 18.66$) for Between judgments, $t(18) = 4.22$, $p < .001$. For response latency, judgments from 0° were also significantly faster than those from 315° for Pre-old judgments, $t(18) = 3.16$, $p = .005$; Between judgments were not significantly different at these imagined headings ($p = .215$). Interaction contrasts indicated no differences between Judgment Types for accuracy ($ps \geq .303$). For latency, the interaction contrast comparing Pre-Old and Post-Old judgments was also not significant ($p = .422$). However, the interaction contrast comparing Pre-Old and Between judgments was significant, $F(1, 18) = 6.67$, $p = .019$, $\eta_p^2 = .270$, indicating that spatial relations for each type may have been coded using different reference frames.

General discussion

Several lines of research have evaluated the circumstances under which previous experiences may, or may not, influence the subsequent coding of spatial information (e.g., Greenauer & Waller, 2010; Kelly & Avraamides, 2011; Kelly & McNamara, 2010; Meilinger et al., 2011; Shelton & McNamara, 2001). The current study serves to elaborate on this work by demonstrating that the potential influence of previous experiences on the formation of an integrated spatial memory will vary depending on contextual factors. In the Introduction we outlined three ways in which spatial information might be integrated across experiences. One possibility is that an existing memory is overwritten by, or reinterpreted in light of, a new experience (accommodation). The strong interpretation of this possibility predicts a single, unified representation with a preferred direction aligned with the new view. The second possibility suggested that an existing memory could drive the interpretation of new experiences, yielding a comparable representation for which the preferred direction corresponds to the initially experienced view (assimilation). Support for accommodation and assimilation mechanisms has been provided by several studies in which participants experienced multiple views of a learning array, but generally demonstrated a preference for judgments aligned with a single viewing orientation (e.g., Kelly & Avraamides, 2011; Kelly & McNamara, 2010; Meilinger et al., 2011). The third possibility suggests that an initial memory is retained more or less in its original form, but integrated as a unit into a more comprehensive representation of the complete array. This hypothesis is consistent with the results reported by Greenauer and Waller (2010) who found that participants established several distinct preferred directions in memory for within and between object-set relations. These authors have suggested that multiple, distinct reference frames may be used to code information at multiple environmental scales and that an integrated representation is established more or less independently of the component representations.

In general, our Main experiment has shown that a previously established representation may have little or no influence on integration processes when there is limited environmental structure and a comparable amount of new spatial information is encountered during each experience. Conversely, our Supplementary Manipulation has shown that an established representation can serve as a basis for integrating new spatial information when these conditions are not met. The totality of our results, however, suggests that the process of relating spatial information acquired across multiple experiences is complex, potentially relying on components outlined by each of the three possibilities to greater or lesser degrees. Below, we briefly review the findings for each judgment type in our Main experiment and discuss which of these three possibilities best accounts for our observations.

The results for Pre-Old judgments in our Main experiment showed that participants demonstrated a clear preference for the 0° imagined heading during the first testing session for the original five objects. Following the second viewing and testing session, Post-Old judgments indicated that preference for the initial view was comparatively weak. Indeed, preference for 0° was supported only by the interaction contrast which indicated that the form of participants' memory was not significantly different between testing sessions. However, the equivalent performance for judgments from the 0° and 315° imagined headings, as well as the significant fits for both the 0° and 315° contrasts, for Post-Old judgments suggests that both experiences may have exerted at least a limited influence on participants memory. One way of accounting for these results is that participants may have retained, more or less in its original form, their memory for the initial viewing experience but supplemented this representation with information acquired during the new experience. Alternatively, it is possible that participants may have reorganized their memory of the original five objects following the second viewing session, but retained a trace of the initial experience. Although the current results are unable to distinguish between these alternatives, we interpret these results as suggesting that the basis for organizing spatial memory need not be restricted to a single preferred heading or experienced view (cf. Shelton & McNamara, 2001). Rather, multiple orientations may be represented with comparable strength in memory (e.g., Mou, Liu, & McNamara, 2009).

Interestingly, a similar supplementation process may have also occurred for new items for which equivalent facilitation was again observed at both experienced headings and both contrasts significantly fit the data. However, unlike the previous comparison, the interaction contrast comparing Pre-Old versus New judgments indicated that the organization of participants' memory was significantly different for these two judgment types. We interpret this result as indicating that participants may have relied primarily on their experience at the second viewing location to organize their memory for the new objects. However, the comparable performance of each contrast to describe response patterns suggests that the perspective aligned with the initial view may have been efficiently represented in memory. We speculate that participants' prior experience with the array may have primed the 0° perspective such that participants could apprehend the new spatial relations, at least partially, from the previously viewed heading. This interpretation is in line with previous findings that have shown that instructions (e.g., Greenauer & Waller, 2008; Mou & McNamara, 2002) or salient environmental structure (e.g., Mou et al., 2009) can facilitate encoding along of non-experienced perspectives. In our experiment it is likely that factors such as the proximity of the previous viewing location and the presence of a partially familiar array (i.e., the Old array serving as contextual cue) may have reinforced or increased the efficiency of priming by the initial experience.

To the extent that neither the first nor the second view was clearly dominant for Post-Old and New judgments, these results can be interpreted as indicating that assimilation and/or accommodation mechanisms may operate simultaneously within spatial configurations. Indeed, Kelly and McNamara (2010) have already provided evidence that assimilation and accommodation mechanisms can be deployed across learning experiences. Our results are in line with this conclusion, but additionally serve to demonstrate that these processes need not be all-or-none. Rather, the dual facilitation for the adjacent experienced views strongly suggests the potential for a bidirectional influence of experiences on memory organization.

In contrast to the within-array findings, however, Between judgments in our Main experiment demonstrated a clear preference for the 315° imagined heading. This result suggests that within-array representations exerted little or no influence on the integration process, in as much as plausible explanations for our within-array findings generally require some influence of both experienced views. If the integration process for Between judgments had been influenced by either within-array representation, we would expect parallel performance patterns to emerge regardless of judgment type. Rather, in line with Greenauer and Waller's (2010) suggestion that spatial information can be coded as distinct units (e.g., arrays) and at different spatial scales (within and between-array), we interpret the lack of facilitation at both headings for between-array judgments as indicating that the spatial integration process for all 10 objects was relatively independent of the processes used to code the relations within either object set or by the initial learning experience (i.e., multiple reference frames).

Despite the fact that several lines of research have previously demonstrated that spatial information is readily integrated across experiences (Greenauer & Waller, 2010; Kelly & Avraamides, 2011; Kelly & McNamara, 2010), it is worth asking whether the current findings necessarily imply that integration between experiences occurred in this experiment. For instance, an alternative explanation could be that each learning experience was represented more or less independently by participants. Indeed, all ten objects were simultaneously available during the second experience, such that Between judgments did not require referencing any aspect of the previously established memory. Thus, participants' ability to make Between judgments could be explained without recourse to any form of integration process. Although a reasonable hypothesis, we do not believe that such an explanation is sufficient to account for the pattern of results observed for Post-Old and New judgments in our Main experiment. Specifically, for both of these judgments, some level of facilitation was observed at both 0° and 315°. If participants established a representation of their second experience which included both arrays, there would be little reason to expect New judgments to show, in addition to facilitation at 315°, a benefit at the initially experienced view of 0°. In addition, although facilitation at 0° and 315° for Post-Old judgments could potentially be explained by participants switching between representations of the two experiences, such a strategy is inefficient (i.e., participants could rely solely on the new representation for all judgments during the second testing phase) and would require the introduction of a mechanism for selecting which representation is accessed for each test trial. In conjunction with the existing literature, we believe that the current pattern of results is more readily and parsimoniously explained in the context of an integration hypothesis.

It is important to note that in our experiments the objects presented during the first learning experience remained available subsequently. Therefore, the second learning experience may have been a privileged orientation for integration inasmuch as it contained all the necessary spatial information to relate the two object arrays without appealing to memory (cf. Kelly & McNamara, 2010; Meilinger et al., 2011). Participants may have found it more efficient to apprehend the initially encoded spatial relations from the novel, and *perceptually supported*, view (accommodation) than to interpret new spatial relations from a *remembered* perspective (assimilation). Although each viewing experience appears to have influenced within-array memory formation, the use of a single reference direction aligned with the second view to establish a global representation of all objects (arguably a more difficult task) may be solely attributable to this perceptual advantage. Thus, whether integration of between-array relations would continue to proceed independently of prior experiences when object relations are no longer perceptually available (i.e., the originally learned items are removed at the second learning experience) remains an open question. This is particularly important as much of the research examining integration has used relatively small configurations of objects that could be apprehended from a single viewing location. Evaluating the extent to which previously observed integration processes can address memory for large, natural environments will be an important direction for future work.

Although the current study serves to provide a preliminary sketch of how spatial information and discrete experiences may be integrated to form a comprehensive spatial memory, our results also highlight a recurring, and as yet unaddressed, issue with the predominant dependent measures used in this and similar research. Theoretically, response latency and pointing accuracy have generally been considered to quantify different aspects of the same memory phenomenon. When retrieving spatial information from a represented (i.e., preferred) orientation, latency indicates participants' facility with accessing their memory and pointing accuracy indicates the fidelity of that memory. As imagined views become increasingly discrepant from the preferred orientation in memory, responses take longer and become less accurate due to the inferential nature of the computational process (Shelton & McNamara, 2001). However, the extant literature provides several examples showing that effects of imagined heading are sometimes most strongly manifest in response latency (e.g., Greenauer & Waller, 2008; Mou et al. 2008; Mou, Liu, & McNamara, 2009; Mou, Zhao, & McNamara, 2007) and at other times in pointing accuracy (e.g., Mou & McNamara, 2002; Mou et al. 2004; Shelton & McNamara, 1997, 2001). Indeed, in the supplementary experiment reported here analyses of response latency may have indicated a trend in the data that was not observed in pointing accuracy. While a thorough treatment of this topic is beyond the scope of the current work, possible explanations for our pattern of results may provide guidance for future work in this area.

In the current experiments the discrepancy in dependent measures is most notable in our Main experiment where Post-Old judgments demonstrated an effect of heading in pointing accuracy but New judgments showed an effect in latency, as well as in Experiment 2 where Between judgments showed an effect of heading only in latency. One possible explanation for these differences it that facilitation in latency is attributable to the view from 315° being most recently experienced (i.e., a recency effect). According to this interpretation the second experienced view may have established a new direction (315°) from which access to the memory was most efficient without necessarily leading to a restructuring, or reorganization, of the memory itself (still organized around a 0° axis). An alternative interpretation, however, could suggest that to the extent that the results of our Main experiment demonstrate a change in memory organization across viewing sessions, the observed difference for Between judgments in our Supplementary Experiment may indicate the beginnings of such a shift. Central to this interpretation is the speculation that although researchers have often assumed that latency and accuracy measure the same mental construct, this need not be the case. Rather, memory access and fidelity, while strongly correlated using our methodology, may reflect only partially overlapping constructs that can be differentially influenced by the transformation process necessary to make judgments from non-represented orientations. According to this view, it is possible that our manipulation influenced one but not the other dependent measure. If so, an intriguing question is whether or not a similar pattern would necessarily emerge in the other dependent measure given longer learning sessions or prolonged testing.

However, the purpose of the current study was not to evaluate the relative influence of learning cues (or learning and testing length) on the organization of spatial memory. Rather, our intent was to evaluate which of the several previously identified integration mechanisms would be engaged under conditions that more closely reflect those encountered in natural situations; specifically, the acquisition of new spatial information following a new experience. To the extent that spatial memory organization is likely influenced by the interaction of many factors, the experiments presented here reflect two relatively simple but extreme scenarios. Regardless, the results of the current study serve to demonstrate both the flexibility and stability of the representational processes that underlie spatial memory. Our Main experiment demonstrates that, at least under these conditions, a previously established memory may have only a limited influence on the coding of spatial information accrued during subsequent experiences. In addition, our findings indicate that that integration of spatial information across experiences may occur relatively independent of the coding of subsets of object relations. However, our supplemental manipulation has also shown that new information can be readily assimilated into existing knowledge structures under some circumstances. Although the necessary conditions under which assimilation will occur remains an open question, we have speculated that the utility of relying on existing memories may be limited to situations in which the majority of the environment has already been learned during a previous experience, salient environmental cues are readily available, or both. Together, these experiments suggest that when presented with substantial new information from a novel view, people will readily commit the additional effort and resources necessary to establish a new, integrated representation of space.

Acknowledgments This research was supported in part by a grant (European Research Commission grant OSSMA 206912) to the third author. We thank Marios Theodorou, Yianna Armosti, Margarita Panayiotou, and Christina Michael for their assistance in conducting these experiments.

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