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Connecting Spatial Memories of Two Nested Spaces

Hui Zhang
Chinese Academy of Sciences

Weimin Mou
University of Alberta

Timothy P. McNamara
Vanderbilt University

Lin Wang
University of Alberta

Four experiments investigated the manner in which people use spatial reference directions to organize spatial memories of 2 conceptually nested layouts. Participants learned directions of 8 remote cities centered to Beijing or Edmonton, where the experiments occurred, using a map or using direct pointing. The map and the environment were aligned, and participants faced north (0°). Participants also learned locations of 7 objects on a table. Participants faced north (0°) during learning but were instructed to learn the layout along the northwest-southeast (45°–225°) axis. Judgments of relative direction (imagine you are standing at X, facing Y, point to Z) were used to determine spatial reference directions in retrieval of bearings between 2 objects or 2 cities. The results showed that when the tested bearing and the imagined heading were within an array, participants used 0° as the reference direction in retrieving bearings between cities but used 45°–225° to retrieve bearings between objects. When the tested bearing and the imagined heading were across 2 arrays, participants used the reference direction of the array from which the tested bearing was. These results indicated that bearings between items within an array were represented only with respect to the reference directions of this array and the relationship between spatial reference directions in these 2 arrays was also represented.

Keywords: spatial memory, spatial reference directions, nested spaces

In the course of everyday life, people need to know the locations of enormous numbers of objects that are placed in nested spaces. For example, an individual may need to know the locations of kitchen appliances in his or her house. The same individual may need to know the location of the house relative to other buildings in the city where he or she is living and the location of the city in terms of other cities in the same state or province. Conceptually, such collections of objects, buildings, and cities can be categorized in a hierarchical structure. The kitchen appliances, at the relative subordinate level, are nested in the house, which together with other buildings are at the relative superordinate level. This study examined the way in which spatial memories of two nested arrays are connected. In particular, we asked how spatial memory of an array at a subordinate level is connected with spatial memory of an array at a superordinate level. The answers to this question can advance our understanding of how spatial memories of different arrays at different conceptual hierarchical levels (objects, buildings, cities) can be connected into comprehensive spatial knowledge of the surrounding environment.

Studies of spatial memory have demonstrated that object arrays at different conceptual hierarchical levels are organized hierarchically in memory (e.g., Hirtle & Jonides, 1985; McNamara, 1986; Stevens & Coupe, 1978). Stevens and Coupe (1978) showed that judgments of spatial relations between cities in different states were biased by the spatial relations between the states. For example, participants tended to judge that San Diego, California was west of Reno, Nevada although the former is east of the latter. This result indicated that spatial relations between locations in different regions (e.g., San Diego and Reno) are not directly or accurately represented and need to be inferred from the spatial relations between the superordinate elements (e.g., California and Nevada). McNamara (1986) showed that spatial memory of objects in the immediate environment is also hierarchical.

Researchers have proposed that the hierarchical structure of spatial memory may result from the use of spatial reference directions at multiple scales (e.g., McNamara, Sluzenski, & Rump, 2008; Meilinger & Vosgerau, 2010; Poucet, 1993). For example, an array of cities may be organized in memory with respect to cardinal reference directions (e.g., north); an array of buildings may be organized with respect to street-aligned reference directions; and an array of objects in a room may be organized with respect to a reference direction intrinsic to that array only (e.g., rows and columns of chairs in a classroom). Orientation depen-

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Hui Zhang, Institute of Psychology, Chinese Academy of Sciences, Beijing, China; Weimin Mou, Department of Psychology, University of Alberta, Edmonton, Alberta, Canada; Timothy P. McNamara, Department of Psychology, Vanderbilt University; Lin Wang, Department of Psychology, University of Alberta.

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Correspondence concerning this article should be addressed to Weimin Mou, P217 Biological Sciences Building, University of Alberta, Edmonton, Alberta, Canada, T6G 2E9. E-mail: wmou@ualberta.ca

dency in judgments of relative direction (e.g., "imagine you are standing at X, facing Y; point to Z") has been used to determine the spatial reference direction in memory. It is hypothesized that spatial relations (e.g., bearings) between objects are specified with respect to reference directions (e.g., Mou, McNamara, Valiquette, & Rump, 2004). In judgments of relative direction, when the imagined heading is parallel to the reference direction, the bearing from the imagined occupied object (e.g., X) to the target object (e.g., Z) is retrieved. In contrast, when the imagined heading is not parallel to the reference direction, the bearing from the imagined occupied object to the target object needs to be inferred with observed extra costs, such as longer latency, larger angular error or both (e.g., Klatzky, 1998).

Using a similar perspective-taking task, Hintzman, O'Dell, and Arndt (1981) found that participants who were located in a particular imagined city (i.e., Mudville) were more efficient pointing to target cities (e.g., Chicago) when facing cardinal directions (north, south, east, west) than when facing noncardinal directions (northwest, southwest, northeast, southeast). This result indicates that people used cardinal directions as reference directions to represent bearing between the imagined occupied city and the target cities. Werner and Schmidt (1999; see also Marchette, Yerramsetti, Burns, & Shelton, 2011; but see Frankenstein, Mohler, Bülthoff, & Meilinger, 2012) reported that pointing to places scattered around an intersection in a familiar city was more efficient from an imagined heading parallel to the streets of the intersection than from an imagined heading misaligned with the streets of the intersection. This result indicated that people established reference directions parallel to the street orientations to represent the bearing between places in the city. Mou and McNamara (2002; see also Greenauer & Waller, 2008, 2010; Mou, Liu, McNamara, 2009) also showed that when participants learned an array of objects in a room, spatial memory was organized with respect to reference directions intrinsic to the array.

It has been proposed that spatial relations between objects within one array of objects are only represented accurately in terms of the reference directions of that array. Spatial relations between objects in one array are not accurately represented in terms of the reference directions of an array at a different hierarchical level. Instead, the spatial relations between the reference directions of arrays at the different levels may be represented accurately to connect spatial memories at different scales (McNamara, Sluzenski, & Rump, 2008; Meilinger & Vosgerau, 2010; Poucet, 1993). For example, spatial relations between buildings might be represented in terms of street-aligned reference directions and spatial relations between objects in a house might be represented in terms of a reference direction intrinsic to the array of objects. However, the spatial relations between objects in the house are not accurately represented with respect to the street-aligned reference directions of the building array and spatial relations between buildings are not accurately represented with respect to the reference direction of the object array. Instead, the relations between the reference direction of the object array and the street-aligned reference direction of the building array might be represented accurately.

This proposed organization of spatial memory is efficient because interobject spatial relations are represented at the conceptual level at which they are most likely to be used (e.g., walking from one house to another). Furthermore, the proposed organization of spatial memory can readily accommodate environmental change. Suppose a road reconstruction project changes the orientation of the street that has been used to establish the street-aligned reference direction of the building array. According to the proposal, this change should not affect the spatial memory of an array at other levels (e.g., the object array in the house). In order to reorganize the spatial memory of arrays at different levels, only the relations between the reference directions of the collection of buildings and the reference directions of the arrays at the other levels (e.g., the object array in the house) need to be updated.

The hypothesis that spatial relations among objects within an array of objects are only represented accurately in terms of the reference directions of that array seems plausible, but to our knowledge, this hypothesis has not been tested directly. In particular, no direct empirical evidence has distinguished this hypothesis from the alternative hypothesis that people may represent spatial relations among objects within one array with respect to multiple reference directions of arrays at different levels.

Two recent studies showed that participants represented spatial relations between two separated object arrays at the same conceptual level (Greenauer & Waller, 2010; Kelly & McNamara, 2010). Greenauer and Waller (2010) demonstrated that participants who learned two arrays that were simultaneously presented close to each other selected two misaligned reference directions, one for each array, as suggested by the results of within array spatial judgments. Also, they reported that participants established a third reference direction to integrate the two arrays together in memory, as suggested by the results of between array judgments. Kelly and McNamara (2010) reported that people tended to use a single reference direction to integrate two arrays of objects that were learned one after the other temporally but mixed with each other spatially. If the results of these two studies using two object arrays at the same conceptual level of space could be extended to the object arrays in two nested spaces, then the hypothesis that spatial relations among objects within an array of objects are only represented accurately in terms of the reference directions of that array might be problematic. Although the findings of Greenauer and Waller (2010) may support the hypothesis, the findings of Kelly and McNamara (2010) do not, because their participants used the reference direction of one array to organize the memories of both arrays.

More relevant to the purpose of the current study, Wang and Brockmole (2003) examined memory of two nested arrays. In one experiment, students who were standing in a lab room pointed without vision to objects in the lab room and to buildings on the campus in which the lab was located. The results showed that students could point to objects in the lab room accurately but had difficulty pointing to campus buildings. Another experiment showed that students were able to point to campus buildings accurately after walking out of the building in which the lab was located. However, at that moment, students could not point to the lab room accurately.

These results indicated that the participants in Wang and Brockmole's (2003) experiments did not represent spatial relations within an array with respect to the reference direction at a different level, supporting the hypothesis that spatial relations among objects within one array are only represented accurately in terms of the reference directions of that array. However, one may argue that participants in the study of Wang and Brockmole did not represent the spatial relations within one array with respect to multiple reference directions at different levels because they never learned the metric relations between two nested spaces (i.e., lab and campus).

As reviewed above, the hypothesis that spatial relations between objects within one array of objects are only represented accurately in terms of the reference directions of that array seems reasonable but lacks empirical evidence. Furthermore, this hypothesis is problematic in the context of inconsistent findings in experiments investigating spatial memory of two separate object arrays at the same conceptual level (Greenauer & Waller, 2010; Kelly & McNamara, 2010).

The purpose of the current project was to test the hypothesis that spatial relations, more specifically the bearings, between objects within one array of objects would only be represented accurately in terms of the reference directions of that array and that spatial relations between the two arrays (e.g., the relations between reference directions) would be represented. We referred to this hypothesis as the *global relation hypothesis*. There are at least two competing hypotheses. One of these hypotheses also stipulates that the bearings between objects within one array of objects are only represented accurately in terms of the reference directions of that array. However, this hypothesis stipulates that the metric relations between two object arrays (e.g., relations between two reference directions) would not be represented. We referred to this hypothesis as the *local-array hypothesis*. The second competing hypothesis is that the bearings between objects within one array are represented with respect to multiple reference directions at different conceptual levels. We referred to this hypothesis as the *across-array hypothesis*.

In Experiments 1–3, participants learned directions of eight remote cities around Beijing, the city in which the experiment was conducted, using a map. The map and the environment were aligned, and participants faced north (0°). Participants also learned locations of seven objects on a table. Participants faced north (0°) during learning but were instructed to learn the layout of objects along the northwest-southeast (45°–225°) axis (Mou, Fan, McNamara, & Owen, 2008). For purposes of exposition, we assume for the moment that under such conditions participants will use north (0°) as the reference direction to represent the bearings between the occupied city (i.e., Beijing) and the remote cities (e.g., Frankenstein et al., 2012).[1] We also assume that participants will use northwest-southeast (45°–225°) axis as the reference direction to represent the bearings between objects (e.g., Mou & McNamara, 2002). Two kinds of judgments of relative direction (imagine you are standing at X, facing Y, point to Z) were used to test the three hypotheses.

In general, in these two types of pointing judgments, the tested bearing and the given heading were from different arrays. In the first kind of judgment, bearings were between cities, at the conceptual superordinate level, and the heading was established by object array, at the conceptual subordinate level. In the second kind of judgment, bearings were between objects, at the conceptual subordinate level, and the heading was established by city array, at the conceptual superordinate level. The three hypotheses would lead to different predictions about the preferred headings in these trials. According to the *local-array hypothesis,* there would be no preferred headings in pointing as participants would not represent any relations between these two arrays and pointing accuracy would be at chance level. According to the *across-array hypothesis,* there would be two preferred headings determined by the reference directions of the two arrays because the tested bearings were represented with respect to the reference directions of both arrays. According to the *global relation hypothesis,* the preferred heading would be determined by the reference direction of the array from which the tested bearing was selected. To judge the tested bearing with respect to a given heading that was established by the other array, participants would use the represented relations between the two arrays (e.g., relations between two reference directions) and translate the given heading established by the other array to the corresponding heading established by the same array from which the bearing was selected. Hence, the preferred heading should be determined by the reference direction of the array from which the bearing was selected.

More specifically, in the first type of trials, participants were oriented to the object array by imagining that they were facing objects but retrieved the bearing between Beijing and remote cities. For example, participants might be asked to imagine standing at object X, facing object Y, and to point to city Z. Note that in this item, the reference point to determine the bearing of the target city was Beijing because the bearing between any object in the small object array and the remote target city was the same as the bearing between the occupied city (i.e., Beijing) and the remote target city. For example, people living in Chicago will point to New York in the same direction whether they are standing in their living room or in their bedroom given the same heading. Hence, the tested bearing is selected from the city array; that is, from Beijing to city Z. The heading is established by the object array; that is from object X to object Y.

According to the *local-array hypothesis,* it is impossible to retrieve the bearing of the target city relative to Beijing from any headings established by the object array, as no metric relations between these two arrays would be represented. According to the *across-array hypothesis,* participants would represent the bearings between Beijing and the remote cities with respect to the reference direction of the object array (e.g., 45°–225° axis) as well as with respect to the reference direction of the city array (e.g., north or 0°–180° axis). Hence, participants should retrieve the bearing of the target city relative to Beijing for the imagined heading of 45° and for the imagined heading of 0° at comparable performance levels. According to the *global relation hypothesis,* participants would represent the bearings between Beijing and the remote cities only with respect to the reference direction of the city array, but the spatial relations between the two arrays (e.g., the relations between two reference directions) would be represented. Participants might translate the heading established by the object array to a heading established by the city array using the represented relations between the two arrays (e.g., by aligning the two arrays so that the reference direction of the object array was 45° counterclockwise relative to the reference direction of the city array). For example, the trial "standing at object X, facing object Y, point to city Z" might be transformed to "standing at Beijing, facing city M, point to city Z'. According to this hypothesis, participants should re-

[1] We acknowledge that because the participants faced north during learning, the reference direction could be due to geography (north) or due to self-orientation (front), the current project could not distinguish these two possibilities.

trieve the bearing of the target city relative to Beijing more easily for the imagined heading of 0° than for the imagined heading of 45°. These trials were used in Experiment 2.

In the second kind of judgment, participants were oriented to the city array by imagining that they were facing cities but retrieved bearings between objects. For example, participants might be asked to imagine standing at object X, facing city Y, and to point to object Z. In these trials, the tested bearing is from the object array; that is, from object X to object Z. The heading is established by the city array; that is, from Beijing to City Y (because the direction from any object in the object array to City Y is the same as the direction from Beijing to City Y).

According to the *local-array hypothesis*, performance should be at chance level for these trials, just as it would be for trials that tested bearings between cities (discussed previously). According to the *across-array hypothesis*, participants should be able to retrieve the bearing between the imagined occupied object and the target object for the imagined heading of 0° (the assumed reference direction of the city array) and for the imagined heading of 45° (the assumed reference direction of the object array) at comparable levels of performance. The reasoning is the same as for trials that tested city-city bearings. According to the *global relation hypothesis,* participants would represent the bearings between objects only with respect to the reference direction of the object array but the spatial relations between the two arrays (e.g., the relations between two reference directions) would be represented. Participants might translate the heading established by the city array to a heading established by the object array using the represented relations between the two arrays. For example, the trial "standing at object X, facing city Y, and point to object Z" might be transformed to the trial "standing at object X, facing object M, point to object Z." Therefore, participants should retrieve the bearing of the target object relative to the locating object more easily for the imagined heading of 45° than for the imagined heading of 0°. These trials were used in Experiment 3.

In the current study, participants were asked explicitly to learn the spatial relations between the object array and the city array. The key assumption underlying the research is that these arrays are nested conceptually. In the global relation hypothesis, we hypothesized that some metric relations between the two arrays were represented. For example, the spatial relations between the two reference directions might be represented. We did not assume, however, that subjects necessarily represented these arrays hierarchically in memory and the experiments did not include direct tests of hierarchical representations (e.g., McNamara, Hardy, & Hirtle, 1989).

Experiment 1 was a control experiment that tested the assumptions that participants used north (0°) as the reference direction to represent the bearings between the occupied city (i.e., Beijing) and the remote cities and used northwest-southeast (45°–225°) axis as the reference direction to represent the bearings between objects.

Experiment 4 was conducted to replicate Experiment 3 when the bearings of the cities were learning by pointing to the cities without reading a map to eliminate the possibility that participants connected memories of the map and object array within the same room instead of the city array and the object array at two different conceptual levels.

Experiment 1

The aim of this experiment was to test whether people could select separate reference directions for two nested arrays. This experiment would provide the foundation to examine how separate reference directions for two nested arrays connect spatial memories of nested arrays in Experiments 2–3.

The two nested arrays were an array of eight cities distributed around Beijing (Figure 1a) and an array of seven objects (Figure 1b) in the lab room located in Beijing. Participants learned the directions of the remote cities relative to the occupied city (i.e., Beijing) by reading a map with north up and learned the object array by viewing the array directly. When studying both arrays, participants were facing north. We expected that participants would represent the bearings of the remote cities relative to Beijing with respect to north because the top of the map is north (e.g., Hintzman et al., 1981; Frankenstein et al., 2012; Rock, 1973). Participants were instructed to learn the object array according to the southeast-northwest direction (e.g., Mou & McNamara, 2002). We expected that participants would represent the spatial layout of

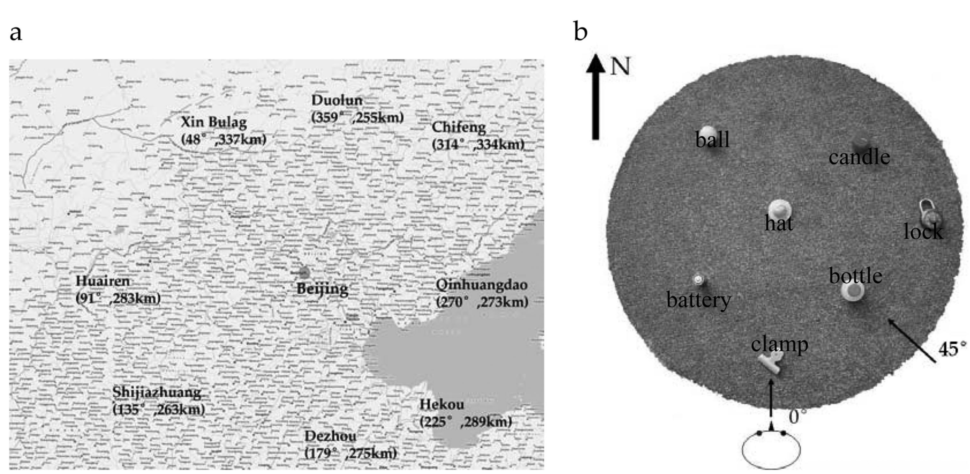

Figure 1. The layouts used in Experiments 1 to 3. a. The map of cities surrounding Beijing. b. The layout of the objects. 0° was the learning viewpoint and 45° was the instructed reference direction.

these seven objects according to the instructed southeast-northwest direction. We labeled the south-north direction as 0° and the southeast-northwest direction as 45°. Judgments of relative direction for each array were used to determine the reference direction of each array. We expected that the preferred imagined headings in judgments of relative direction should be aligned with 0° (north) for the city array (0°, 90°, 180°, and 270°) and that the preferred imagined heading in judgments of relative direction should be aligned with 45° for the object array (45°, 135°, 225°, and 315°) as a saw-tooth pattern (both in terms of latency and pointing error) across imagined heading has been well documented (e.g., Greenauer & Waller, 2010; Hintzman et al., 1981; Mou & McNamara, 2002). The saw-tooth pattern might be caused by the existence of a single dominant reference direction (e.g., 45°) and ease of transformation at the aligned headings (e.g., 135°, 225°, and 315°; see Street & Wang, 2012).

Method

Participants. Sixteen university students (eight men and eight women) participated in the study in return for monetary compensation.

Materials and design. The small object layout was placed in a cylindrical room 3.0 m in diameter constructed from a reinforced cloth and a black fabric. As illustrated in Figure 1b, a circular table top covered by a grey mat (80 cm in diameter) was laid on the floor at the center of the room. Seven common objects were placed on the table. The configuration of these objects was the same as in Mou and McNamara's (2002) Experiment 3. The distances between lock-candle and lock-bottle were 16 cm to indicate the size of the object array. Participants were instructed to learn the object array along the direction of 45° (lock-candle; bottle-hat-ball, and clamp-battery) when standing at the position marked as 0°, facing north.

The map was printed out in black and white format on A4 paper (Figure 1a). The eight cities used in the experiment were chosen to correspond to eight bearings from Beijing (north, south, east, west, northeast, northwest, southeast, and southwest) and to be far from Beijing (more than 250 km). All cities were less than 3° away from these directions (e.g., Duolun was 1° from north). Participants, facing north, were instructed to learn the directions of these eight cities with respect to Beijing.

Two test blocks were conducted. The first block only tested spatial memory of the city array and the second block only tested spatial memory of the object array.[2]

In the first block, the default occupied place was Beijing; for example, "Imagine you are facing Duolun. Point to Dezhou." The first city (e.g., Duolun) established the imagined facing direction (north) and the second city was target (e.g., Dezhou). Participants were given a total of 64 trials defined by crossing imagined heading (eight cities) and pointing direction (eight cities).

In the second block, each trial was constructed from the names of the seven common objects placed on the circular table and required participants to point to an object as if they were standing in the display; for example, "Imagine you are at Bottle facing Candle. Point to Hat." The first two objects established the imagined standing location and facing direction (e.g., Bottle and Candle) and the third object was the target (e.g., Hat). Participants were given a total of 48 trials, six trials at each of the eight imagined headings. These trials were chosen following the same rules as Mou and McNamara (2002): (a) three pairs of standing objects and facing objects were used for each heading; (b) two target objects were used in each direction of front, sides, and back; (c) of the six target objects used for each heading, one was pointed to twice; and (d) across all headings, each object was used nearly the same number of times as the standing, facing, and pointing objects, respectively. Participants used a joystick to make pointing responses.

The primary independent variable was imagined heading. Headings were arbitrarily labeled counterclockwise from 0° to 315° in 45° steps beginning with the position labeled 0° (north) in Figure 1b. As shown in the figure, 0° corresponds to the heading facing north (Duolun) in the first test block and all the headings parallel to the arrow labeled 0° in the second block (e.g., standing at bottle facing candle; standing at clamp facing hat). The imagined heading of 45° corresponds to northwest in the first test block (Xin Bulag) and all headings parallel to the arrow labeled 45° in the second block (e.g., standing at lock facing candle; standing at bottle facing hat).

The dependent measures were absolute angular error and response latency. Absolute angular error was measured as the absolute difference between the correct direction and estimated direction of the target. Response latency was measured as the time from presentation of the target object names to the pointing response.

Previous studies have revealed a saw-tooth pattern (in terms of both latency and error) across imagined headings (e.g., Greenauer & Waller, 2010; Hintzman et al., 1981; Mou & McNamara, 2002). In this and following experiments, latency and angular error for the imagined headings aligned with 0° (0°, 90°, 180°, and 270°) were compared to those for the imagined headings aligned with 45° (45°, 135°, 225°, and 315°). The reference directions are determined to be aligned with 0° if either latency or angular error is smaller at the imagined headings aligned with 0°, and there was no latency-angular error tradeoff. The reference directions are determined to be aligned with 45° if either latency or angular error is smaller at the imagined headings aligned with 45°, and there is no latency-angular error tradeoff. The reference directions could not be determined if both variables showed no difference between 0° aligned imagined headings and 45° aligned imagined headings or if there were latency-angular error tradeoff.

Procedure.

Learning phase. Participants first received instructions on using the joystick. After they were able to use the joystick, they were then led to the cylindrical room and placed at the viewing position (0° in Figure 1b) facing north. The direction of north was explicitly pointed out to participants. Then participants were asked to learn the directions of eight cities using the map. The participants viewed the map for 30 s. Then they were asked to name and point to each city in the physical directions in any order. Hence, participants had opportunities to learn the physical directions of the cities with respect to their learning location and orientation.

Five study-test trials were conducted and all participants were able to point to the directions of all the cities accurately. The map

[2] We conducted another experiment that tested object array first, and the results were the same indicating the test order does not matter. For the interest of brevity, we do not report that experiment.

was then taken away, and participants were instructed to stand still and learn the locations of the object array along the 45°–225° direction, as indicated by the experimenter (e.g., lock-candle; bottle-hat-ball; clamp-battery). The participants viewed the display for 30 s and then named and pointed to objects in the order consistent with the 45°–225° direction with their eyes closed. Each time after participants named and pointed to the objects, they were asked to name and point to the directions of the remote cities once again so that participants could explicitly learn the metric relations between city array and object array. Five study-test trials were conducted.

Testing phase. After the learning session, participants were taken to another room to be tested. Participants first were instructed to complete the task only using the cities they had learned. After they finished the first block, participants were instructed to complete the task only using the objects in the object array. Participants were blindfolded during the testing phase. Seated in a chair, the participant wore an earphone and held a joystick. The test trials were presented via the earphone attached to a PC computer. The participant first initiated each trial by pressing a button of the joystick. Trials proceeded as follows: The imagined heading was given aurally (e.g., "Imagine you are facing Duolun" in the first block or "Imagine you are standing at the bottle facing the hat" in the second block). The participant was instructed to pull the joystick trigger when he or she had a clear mental image of where he or she was standing and the direction he or she was facing. The target item was immediately presented aurally when the participant pulled the trigger (e.g., "Point to Xin Bulag" in the first block or "Point to the Candle" in the second block). The participant used the joystick to point to where the target would be if he or she occupied the standing location and facing direction as presented. The participant was instructed to hold the joystick exactly in the front of his or her waist and keep the joystick forward when he or she pointed. Pointing accuracy was emphasized ("please point only after you are sure where the target is").

Results

Pointing latency and angular error were analyzed in repeated-measure analyses of variance (ANOVAs) with terms for imagined heading (0° to 315° in 45° steps). There was no evidence of speed–accuracy trade-offs.

City array. Mean pointing latency is plotted in Figure 2 as a function of imagined heading. As illustrated in the figure, participants were faster pointing to cities for the imagined headings of 0°, 90°, 180°, and 270°, which were aligned with the assumed frame of reference defined by the north-south, east-west, than for the imagined headings of 45°, 135°, 225°, and 315. The overall effect of imagined heading on pointing latency was significant, $F(7, 105) = 10.29$, $p < .001$, $MSE = 3.54$. The planned comparisons showed that pointing latency for the headings of 0°, 90°, 180°, and 270° was shorter than for the headings of 45°, 135°, 225°, and 315°, $t(105) = 4.82$.

Mean angular error is presented in Table 1 as a function of imagined heading. The overall effect of imagined heading on pointing error was significant, $F(7, 105) = 3.02$, $p < .01$, $MSE = 103.43$. There was no significant difference in pointing error between the imagined headings of 0°, 90°, 180°, and 270° and the imagined headings of 45°, 135°, 225°, and 315°, $t(105) = 1.51$.

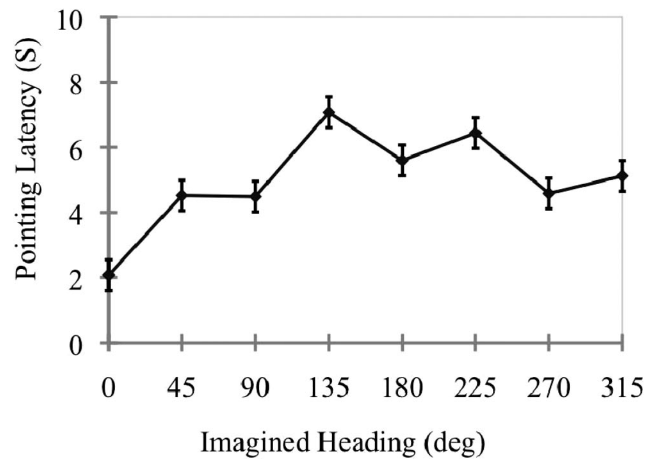

Figure 2. Response latency in the city array as a function of imagined heading in Experiment 1. (Error bars are ±1 standard error of the mean after removing the individual variation, as estimated from the analysis of variance.)

In this experiment, latency was more sensitive than pointing error to imagined heading. No trade-off was found between the pointing latency and pointing error. The Pearson correlation between the mean pointing latency and mean pointing error across imagined headings was 0.86. The latency results indicate that participants might have encoded the spatial structure of the cities on the map in terms of the cardinal directions, 0°–180° (north-south).

Object array. Mean pointing latency is plotted in Figure 3 as a function of imagined heading. Pointing latency was shorter for the imagined headings of 45°, 135°, 225°, and 315°, which were aligned with the assumed frame of reference defined by the symmetric axis of the object array than for the imagined headings of 0°, 90°, 180°, and 270°. The overall effect of imagined headings was significant, $F(7, 105) = 6.84$, $p < .001$, $MSE = 5.33$. The planned comparisons showed that pointing latency for the imagined headings of 45°, 135°, 225°, and 315° was shorter than for the imagined headings of 0°, 90°, 180°, and 270°, $t(105) = 4.38$.

Mean pointing error is presented in Table 1 as a function of imagined heading. The overall effect of imagined heading on pointing error was significant, $F(7, 105) = 2.43$, $p < .05$, $MSE = 104.26$. Planned comparisons showed that pointing error at the headings of 45°, 135°, 225°, and 315° was smaller than pointing error at the headings of 0°, 90°, 180°, and 270°, $t(105) = 2.85$.

No trade-off was found between pointing latency and error. The Pearson correlation between mean pointing latency and mean pointing error across imagined headings was 0.61. These results indicate that participants might have encoded the spatial structure of the object array in terms of reference axes aligned with the symmetric axis, 45°–225° (southeast-northwest).

Discussion

Participants encoded the bearings between the occupied city (i.e., Beijing) and the remote cities in terms of the axes of 0°–180° (north-south). Participants encoded the spatial structure of the layout of the objects in terms of the axes of 45°–225° (southeast-

Table 1
Mean Angular Error (in Degrees) as a Function of Imagined Heading for Each Experiment

	Imagined headings															
	0°		45°		90°		135°		180°		225°		270°		315°	
Experiment no.	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
1																
City array	11	6	17	10	21	13	23	18	20	15	25	17	17	16	16	13
Object array	25	13	23	12	30	10	26	10	30	13	26	11	34	17	23	11
2	24	11	21	12	31	16	33	19	28	19	28	22	30	16	28	13
3	25	16	33	17	43	17	40	22	39	19	48	13	42	9	38	10
4	30	13	36	12	40	15	44	18	47	15	46	18	41	21	42	25

northwest). Accordingly, participants could establish two misaligned reference frameworks, one for each array (Greenauer & Waller, 2010). Experiments 2 and 3 tested whether and how participants represented metric relations between the city array and the object array.

Experiment 2

In Experiment 2, participants adopted imagined headings established by objects but retrieved bearings of the remote cities with respect to the occupied city (i.e., Beijing; e.g.,"Imagine you are at Bottle facing Candle, Point to Duolun."). The logic for this particular trial was discussed in the Introduction. According to the *global relation hypothesis*, participants would represent bearings between the occupied city (i.e., Beijing) and target cities (e.g., Duolun) with respect to the reference direction of the city array (i.e., 0° or north) only. Participants also would represent spatial relations between the two arrays. Hence, participants should point to the target city (e.g., Duolun) from the occupied city (i.e., Beijing) better for the imagined headings aligned with 0° than for the imagined headings aligned with 45°. According to the *across-array hypothesis*, participants would represent bearings between the occupied city (i.e., Beijing) and target cities (e.g., Duolun) with respect to the reference directions of both arrays of objects and cities. Therefore, pointing performance to the target city should be at comparable levels for the imagined headings aligned with 0° and for the imagined headings aligned with 45°, in other words, a flat function. According to the *local-array hypothesis*, participants would not represent spatial relations between these two arrays (Wang & Brockmole, 2003). Hence, pointing performance to the target city should be at chance level for the imagined headings aligned with 0° and for the imagined headings aligned with 45°.

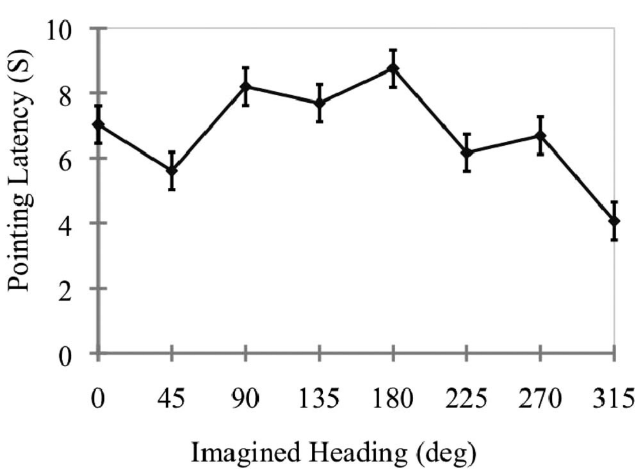

Figure 3. Response latency in the object array as a function of imagined heading in Experiment 1. (Error bars are ±1 standard error of the mean after removing the individual variation, as estimated from the analysis of variance.)

Method

Participants. Sixteen university students (eight men and eight women) participated in the study in return for monetary compensation.

Materials and design. The materials were the same as those of Experiment 1.

Only one test block was conducted. Each trial was constructed from the names of eight cities and the seven objects of the object array. Participants were required to point to a city as if facing a particular direction given by two objects; for example, "Imagine you are at Bottle facing Candle, Point to Duolun." The imagined occupied object (e.g., Bottle) and the imagined facing object (e.g., Candle) established an imagined heading. Because the size of the object array was much smaller than the distance between the occupied city and the target city (about 0.5 m vs. 250,000 m), the bearing between the imagined occupied object (e.g., Bottle) and the target city (e.g., Duolun) was the same as the bearing between the occupied city (i.e., Beijing) and the target city. Because of this affinity, participants retrieved the bearing between cities (e.g., Duolun relative to Beijing) with respect to the directions specified in the objects array.

Participants were given a total 192 trials, 24 trials at each of the eight imagined headings. These trials were chosen such that (a) three pairs of standing objects and facing objects were used for each imagined heading as in Experiment 1; (b) for each pair, all eight target cities were used.

The primary independent variable was imagined heading. Eight equally spaced headings were used (0–315° in 45° increments). The dependent measures were pointing latency and absolute pointing error.

Procedure. The practice and learning phases were the same as in Experiment 1. After participants were guided into the testing room, they were tested with the trials described above. As in Experiment 1, participants learned the objects array after learning the cities by reading a map. The participants viewed the display for 30 s and then named and pointed to objects in the order consistent with the 45°–225° direction with their eyes closed. Each time after participants named and pointed to the objects, they were asked to name and point to the directions of the remote cities once again so that participants could explicitly learn the metric relations between city array and object array. Therefore, participants still could use the reference direction of the object array to reorganize the memory of the city array.

Results and Discussion

Pointing latency and pointing error were analyzed in repeated-measure ANOVAs with terms for imagined heading (0° to 315° in 45° steps). Mean pointing latency is plotted in Figure 4 as a function of imagined heading. The overall effect of imagined heading was significant, $F(7, 105) = 10.25$, $p < .001$, $MSE = 0.52$. The planned comparisons showed that pointing latency for the imagined headings of 0°, 90°, 180°, and 270° was shorter than latency for the imagined headings of 45°, 135°, 225°, and 315°, $t(105) = 5.02$.

Mean pointing error is presented in Table 1 as a function of imagined heading. The overall effect of imagined heading was significant, $F(7, 105) = 2.38$, $p < .05$, $MSE = 101.21$. The planned comparisons showed no difference between the pointing error for the imagined headings of 0°, 90°, 180°, and 270° and pointing error for the imagined headings of 45°, 135°, 225°, and 315°, $t(105) = 0.22$. Post hoc comparisons showed that pointing error for the imagined heading of 0° was significantly smaller than for the imagined heading of 90° and 135°, $t(105) \geq 1.97$.

No trade-off was found between pointing latency and pointing error. The Pearson correlation between mean pointing latency and mean pointing error across imagined headings was 0.46.

These results showed that when the imagined heading was established by two objects and the tested bearing was between two cities, the preferred imagined headings were aligned with the reference directions of the city array supporting the *global relation hypothesis*.

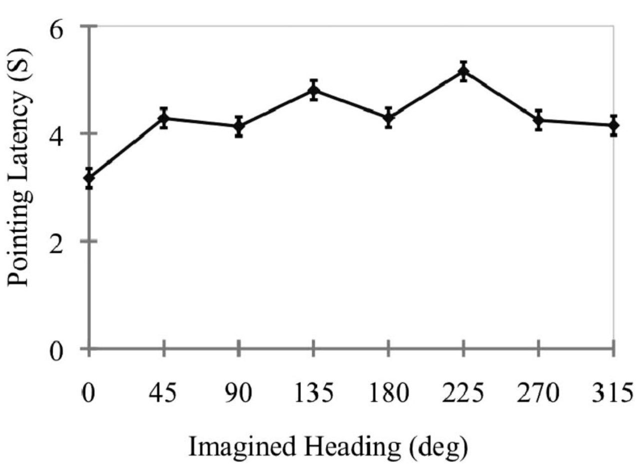

Figure 4. Response latency as a function of imagined heading in Experiment 2. (Error bars are ±1 standard error of the mean after removing the individual variation, as estimated from the analysis of variance.)

Experiment 3

In Experiment 3, participants adopted an imagined heading of facing a city but retrieved bearings between two objects ("Imagine you are at Bottle facing Duolun, Point to Candle."). The logic for this type of test trial was discussed in the Introduction. According to the *global relation hypothesis*, participants should point to the target object better for the imagined headings aligned with 45° (the assumed reference direction of the object array) than for the imagined headings aligned with 0° (the assumed reference direction of the city array). The *local-array hypothesis* predicts that performance should be at chance level for the imagined headings aligned with 45° and for the imagined headings aligned with 0°. The *across-array hypothesis* predicts comparable performance for the imagined headings aligned with 45° and for the imagined headings aligned with 0°, producing a flat pattern.

Method

Participants. Sixteen university students (eight men and eight women) participated in the study in return for monetary compensation.

Materials and design. The materials were the same as those of Experiment 1.

Only one test block was conducted. Participants were required to point to one target object from another imagined occupied object as if facing a particular direction of a city; for example, "Imagine you are at Bottle facing Duolun, Point to Candle." Because the size of the object array is much smaller than the distance between the occupied city (i.e., Beijing) and the city of the imagined facing direction (about 0.5 m vs. 250,000 m), the heading from the imagined occupied object (e.g., Bottle) to the imagined facing city (e.g., Duolun) is the same as the imagined heading from the occupied city (i.e., Beijing) and the imagined facing city (e.g., Duolun). The imagined occupied object and the target object established the tested bearing between two objects. Participants needed to retrieve the bearings between the objects with respect to the directions from Beijing to the remote cities.

Participants were given a total 48 trials, six trials at each of the eight imagined headings. These trials were chosen such that (a) three pairs of standing objects and facing cities were used for each heading; (b) in each pair two target objects were used.

The primary independent variable was imagined heading. Eight equally spaced headings were used (0–315° in 45° increments). The dependent measures were response latency and absolute pointing error.

Procedure. The practice and learning phases were the same as in Experiment 1. After participants were guided into the testing room, they were tested with the trials described above.

Results and Discussion

Pointing latency and pointing error were analyzed in repeated-measure ANOVAs with terms for imagined heading (0° to 315° in 45° steps). Mean pointing latency is plotted in Figure 5 as a function of imagined heading. The overall effect of imagined heading was significant, $F(7, 105) = 2.9$, $p < .01$, $MSE = 7.30$. The planned comparisons showed that pointing latency for the imagined headings of 45°, 135°, 225°, and 315° was shorter than

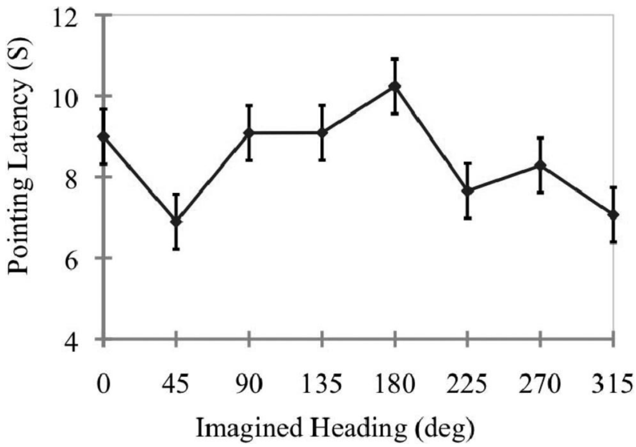

Figure 5. Response latency as a function of imagined heading in Experiment 3. (Error bars are ±1 standard error of the mean after removing the individual variation, as estimated from the analysis of variance.)

latency for the imagined headings of 0°, 90°, 180°, and 270°, $t(105) = 3.08$.

Mean pointing error is presented in Table 1 as a function of imagined heading. The overall effect of imagined heading was significant, $F(7, 105) = 3.61$, $p < .01$, $MSE = 214.33$. There were no significant differences between the pointing errors for the imagined headings of 45°, 135°, 225°, and 315° and pointing errors for the imagined headings of 0°, 90°, 180°, and 270°, $t(105) = 0.87$. Post hoc comparisons showed that pointing error for the imagined heading of 45° was significantly smaller than for the imagined heading of 90° and 225°, $t(105) \geq 1.97$.

No trade-off was found between pointing latency and pointing error. The Pearson correlation between mean pointing latency and mean pointing error across imagined heading was 0.01.

The results showed that when the imagined heading was effectively defined by two cities and the tested bearing was between two objects, the preferred imagined headings were aligned with the reference directions of the object array, supporting the *global relation hypothesis*.

Experiment 4

In the previous experiments, participants learned the city array from a map. This aspect of the method might have produced memories of two arrays at the same conceptual level, as both of them were perceived within the learning room. In Experiment 4, participants learned the directions of cities by pointing to their physical locations instead of learning a map to remove the influence of perceiving the map within the room. This experiment was conducted in Edmonton, Alberta, Canada for convenience in collecting data. The testing items were similar to those used in Experiment 3 (e.g., "Imagine you are at Bottle facing Athabasca, Point to Candle").

Method

Participants. Sixteen university students (eight men and eight women) university students from introductory psychology classes at the University of Alberta participated in this experiment. They received partial course credit for their participation.

Materials and design. The object array was the same as the one used in Experiment 1. The object layout was placed in a cylindrical room 4.0 m in diameter constructed from reinforced cloth and black fabric. The eight cities around Edmonton, where this experiment was conducted, corresponded to eight bearings from Edmonton (north, south, east, west, northeast, northwest, southeast, and southwest; see Figure 6) and are far from Edmonton (from 148 to 219 km). All cities were less than 5° away from the corresponding directions (e.g., Athabasca was 5° from north). While facing north, participants were instructed to learn the directions of these eight cities with respect to Edmonton by pointing to the cities under the experimenter's direction.

Procedure. Before the experiment started, the experimenter read the names of the eight cities aloud to the participants and asked them if they had heard of any of these cities in order to encourage participants to be aware that these cities are round Edmonton. In the learning phase, the participants learned the directions of the eight cities by physically pointing to them with the guidance of the experimenter. The experimenter showed participants the directions of the cities at the beginning of the learning session. Then participants memorized the directions of the cities. After 30 s retention, participants named and pointed to each of the eight directions using their arms. The experimenter corrected participants' pointing if necessary. After five times of learning-pointing sessions, participants started to learn the object array. Otherwise, the procedure of this experiment was identical to that of Experiment 3.

Results and Discussion

Pointing latency and pointing error were analyzed in repeated-measure ANOVAs with terms for imagined heading (0° to 315° in 45° steps). Mean pointing latency is plotted in Figure 7 as a function of imagined heading. The overall effect of imagined heading was significant, $F(7, 105) = 2.8$, $p < .01$, $MSE = 2.87$. The planned comparisons showed that pointing latency for the imagined headings of 45,135, 225, and 315 was shorter than

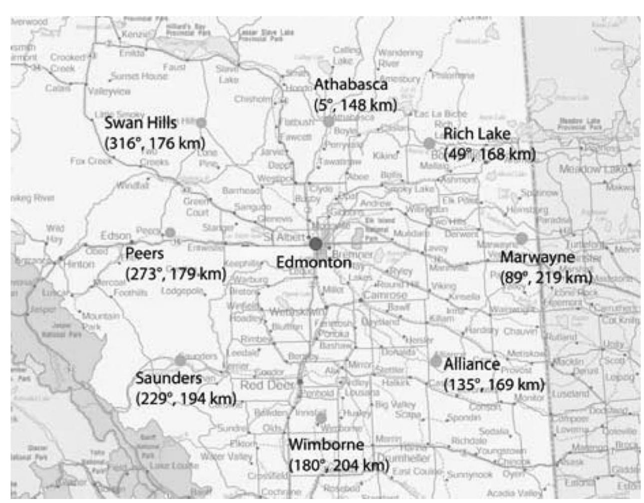

Figure 6. The city layout used in Experiment 4.

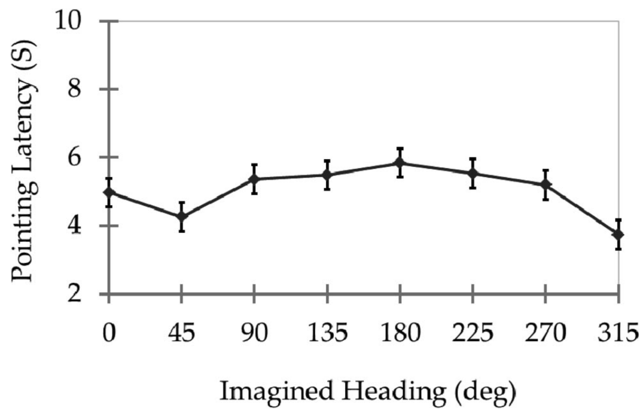

Figure 7. Response latency as a function of imagined heading in Experiment 4. (Error bars are ± 1 standard error of the mean after removing the individual variation, as estimated from the analysis of variance.)

latency for the imagined headings of 0, 90, 180, and 270, $t(105) = 1.97$, $p = .05$. As illustrated in Figure 7, the saw-tooth pattern in this experiment was not as apparent in this experiment as in the previous experiments. Hence, we compared latency for the imagined heading of 45 with that for the imagined headings of 0, 90, 180, and 270. The former was significantly shorter than the latter, $t(105) = 2.29$, $p < .05$.

Mean pointing error is presented in Table 1 as a function of imagined heading. The overall effect of imagined heading was significant, $F(7, 105) = 2.14$, $p < .05$, $MSE = 242.38$. There were no significant differences between the pointing errors for the imagined headings of 45, 135, 225, and 315 and pointing errors for the imagined headings of 0, 90, 180, and 270, $t(105) = 0.88$. Post hoc comparisons showed that pointing error for the imagined heading of 45° was significantly smaller than for the imagined heading of 180°, $t(105) = 2.00$.

No trade-off was found between pointing latency and pointing error. The Pearson correlation between mean pointing latency and mean pointing error across imagined heading was 0.44.

The results showed that when the imagined heading was effectively defined by the bearing of two cities and the tested bearing was between two objects, the preferred imagined headings were aligned with the reference directions of the object array, replicating the results of Experiment 3.

General Discussion

This project investigated how spatial memories of two conceptually nested arrays of objects are interrelated when the metric relations between the two arrays are explicitly learned. We conjectured that people would not represent bearings between items with respect to the reference direction of an array at another conceptual level. Instead, they might connect spatial memories of two conceptually nested arrays by representing spatial relations between reference directions of two nested arrays (e.g., McNamara et al., 2008; Poucet, 1993). This conjecture was referred to as the *global relation hypothesis*. Two competing hypotheses were also tested. The *local-array hypothesis* stipulated that the bearings between items within one array are represented with respect to the reference direction of that array only and that the spatial relations between the two nested arrays (e.g., the relations between the reference directions) are not represented. The *across-array hypothesis* stipulated that the bearings between items within one array are represented with respect to multiple reference directions of the arrays at different levels. The findings of this project supported the *global relation hypothesis*.

The results of Experiment 1 indicated that participants used north as a reference direction for the city array, whereas participants used the symmetric axis of the object array (i.e., 45° counterclockwise with respect to north) as the reference direction for the object array. In Experiment 2, participants adopted an imagined heading from one object to another object and retrieved the bearings from Beijing to the remote cities. In Experiment 3, participants adopted an imagined heading from Beijing to one of the remote cities and retrieved the bearings between two objects. The results showed that the preferred imagined heading was parallel to the reference direction of the remembered array from which the bearing information rather than heading information was retrieved. In particular, when the heading was established by the object array (e.g., at lock, facing candle), and the bearing was retrieved from the remembered city array (e.g., point to Duolun from Beijing), the preferred imagined headings were aligned with the reference directions of the city array (Experiment 2); and when the heading was established by the city array (e.g., at Beijing, facing Duolun), and the bearing was retrieved from the remembered object array (e.g., point to candle from lock), the preferred imagined headings were aligned with the reference directions of the object array (Experiment 3). The same results were observed whether participants learned the city array from a map (Experiment 3) or by manually pointing to surrounding cities (Experiment 4).

The findings of this project did not support the *across-array hypothesis*, which stipulates that participants might represent bearings between items within one array with respect to the reference directions of both nested arrays. This hypothesis predicted that performance should be at comparable levels for the imagined headings parallel to the reference direction of the object array and for the imagined headings parallel to the reference directions of the city array. Wang and Brockmole (2003) also reported that participants might not represent bearings between items within one array with respect to the reference directions of both nested arrays. However, their results also indicated that participants might not represent spatial relations between two nested arrays, consistent with the *local-array hypothesis*. The findings of the current study, however, indicated that participants did represent spatial relations between nested arrays; otherwise, performance would be at chance level for the imagined headings parallel to the reference direction of the object array and for the imagined headings parallel to the reference directions of the city array.

There are many possible ways that metric relations between the city array and object array could be represented. Here we discuss two proposals that have been documented in the literature.

Greenauer and Waller (2010) proposed that participants used a macro reference direction to integrate two separate object arrays and that the macro reference direction could differ from each of the micro reference directions used to organize memories of the individual arrays. This proposal may not generalize to conceptually nested arrays. If one macro reference direction was used to integrate the city array and object array, then the preferred imagined heading should have been the same in Experiments 2 and 3 because the trials in both experiments were about judgments between arrays. However, the results of Experiments 2 and 3 showed that the preferred imagined heading was parallel to the reference direction of the remembered array from which the bearing information rather than heading information was retrieved.

Another possible explanation of the findings is that participants represented the metric relations between the reference directions of these arrays (e.g., McNamara et al., 2008; Meilinger & Vosgerau, 2010; Poucet, 1993). Specifically, participants might represent that the symmetric axis of the object array was 45° counter clockwise relative to north and that north was 45° clockwise relative to the symmetric axis of the object array. In Experiment 2, when participants needed to compute the bearing between the target city and Beijing with respect to an imagined heading established by two objects, they might have first translated the imagined heading in the object array to an imagined heading in the city array given the relation between the reference directions of the two arrays. For example for the trial "at lock, facing candle, point to Hekou" (see Figure 1), participants translated the imagined heading to "at Beijing, facing Xin Bulag, point to Hekou." This translation was possible because the heading "at lock, facing candle" was parallel to the reference direction of the object array; the reference direction of the object array was 45° counter clockwise with respect to the reference direction of the city array; and the bearing of "Xin Bulag" was 45° counter clockwise relative to the reference direction of the city array. Hence, a judgment of the bearing of the target city given an imagined heading established by two objects was translated to a judgment of the bearing of the target city in the representation of the city array, as in Experiment 1. Consequently, the preferred imagined heading was parallel to the reference direction of the city array rather than the reference direction of the object array as shown by the results of Experiment 2. The same analyses can be used to explain results of Experiments 3 and 4.

According to this conjecture, there would be extra between-array translation costs in the judgments between two arrays relative to judgments within arrays. We compared the mean latency and mean error of all imagined headings in Experiment 1 (within arrays) to those in Experiments 2 and 3 (between arrays). Although there was no significant difference in terms of latency (5.9 s vs. 6.3 s), pointing error was significantly smaller in Experiment 1 than in Experiments 2 and 3 (23° vs. 33°), $t(62) = 3.73$, $p < .001$. This conjecture therefore was supported by the findings of the current study.

The discrepancy between the current findings and those of Wang and Brockmole (2003) can be easily reconciled given the different learning methods in these two studies. In the current experiments, participants were encouraged to learn the spatial relations between the two arrays during learning. Participants learned both arrays at the same position and from the same orientation. Furthermore, for five study-test trials, after participants pointed to objects, they also pointed to cities from the same position and orientation. In contrast, participants in Wang and Brockmole's (2003) study were not explicitly asked to learn the spatial relations between the object array and the building array, and given the spaces involved (college campus and unfamiliar laboratory room), it is unlikely they would have known these relations prior to the experiment. They would have had to rely on path integration and online inference to determine the spatial relations between the laboratory room and the campus as they locomoted between them. This explanation finds support in Greenauer and Waller's (2010) study. Participants represented metric relations between two object arrays when they learned the two object arrays in the same room from the same learning position and orientation. As long as people can learn the metric relations between two arrays, people might be able to represent metric relations between them whether both arrays are placed in the same room or one is room-sized and the other is a remote array.

Why do people only represent spatial relations between the reference directions of two arrays rather than represent spatial relations in each array in terms of the reference directions in both arrays? There is ample evidence that spatial memories are organized hierarchically (e.g., Hirtle & Jonides, 1985; McNamara, 1986; Stevens & Coupe, 1978). In a hierarchical spatial memory, spatial relations between two objects within an array are accurately represented. Spatial relations between two objects in different arrays at the same hierarchical level are not accurately represented. However, spatial relations between the arrays, at the higher level, are represented. Spatial relations between two objects at the lower level in two different arrays can be inferred from the spatial relations between the arrays. In this way, representing spatial relations is efficient. Furthermore, modifying the spatial relations at one level will not necessarily change the spatial relations at the other level. For example, rearranging the furniture within one room of a house does not necessitate relearning the spatial relations between each piece of furniture and the frames of reference used in other rooms of the house.

In the current project, we examined two arrays in conceptually nested spaces but cannot verify that participants represented the arrays in memory hierarchically. So how did participants perceive and represent these two arrays? More specifically, did participants perceive and represent these two arrays as two unrelated arrays? The answer to this specific question is negative. If there were no represented relations between the object array and the city array, participants would have performed at chance level (90°), yet the mean error ranged from 21° to 48° in Experiments 2–4 (see Table 1). This result clearly indicates that people could calculate bearings between cities in terms of the heading specified by object pairs and vice versa. Then did participants perceive and represent these two arrays as two arrays at the same conceptual level? The answer to that question also appears to be negative. The results in the current article differed from those in the studies using two objects arrays that were placed at the same conceptual level (Greenauer & Waller, 2010; Kelly & McNamara, 2010). Kelly and McNamara (2010) showed that when participants learned two object arrays one after the other, they used the reference direction of the first array to organize memory of the second array. Greenauer and Waller (2010) found that participants used a macro reference direction to represent the relations between the two object arrays. Regardless of the differences between these two studies, both predicted that participants would have the same preferred imagined headings in Experiments 2 and 3 in the current study. The current study showed, however, that the preferred reference direction depended on whether the target object belongs to the city array or the object array. This contrast between, on the one hand, the findings of Greenauer and Waller and of Kelly and McNamara and, on the other hand, those of the current study lead us to conjecture that the city and object arrays were represented at different conceptual levels. However this conjecture requires a direct test.

In summary, the current project showed that participants were best at judging bearings between objects when the imagined heading was parallel to the hypothesized reference direction of the object array and best at judging bearings between cities when the imagined heading was parallel to the hypothesized reference direction of the city array, regardless of whether the imagined heading and the tested bearing were in the same array or in two nested arrays. These findings indicated that people establish separate reference directions for two conceptually nested arrays to organize spatial memory of each array. Furthermore, to the extent that people learn spatial relations between two arrays, they seem to represent the spatial relations between the reference directions of the two arrays but not represent spatial information within each array in terms of both reference directions.

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