

Human Navigation in Nested Environments

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Navigation in humans and many other animals relies on spatial representations of their environments. Three experiments examined how humans maintain sense of orientation between nested environments. Subjects can acquire new spatial representations easily without integrating them into their existing spatial knowledge system. While navigating between nested environments, subjects seemed to constantly switch between the currently processed environment by reorienting to approaching environments and losing track of old environments at given spatial regions. These results suggest that spatial updating in naturalistic, nested environments does not occur for all environments at the same time. Implications for the hierarchical theory of spatial representations and the path integration theory of navigation are discussed.

Various animals demonstrate astonishing navigation abilities. For example, creatures as simple as ants can travel 1,000 times their body length in random, zigzagging paths and return home in a straight line (e.g., Müller & Wehner, 1988, 1994; Wehner & Srinivasan, 1981). This remarkable ability, referred to as path integration, has been found in insects, birds, rodents, and humans (Alyan & McNaughton, 1999; Berthoz, Israel, Francois, Grasso, & Tsuzuku, 1995; Collett, 1996; Etienne, Maurer, & Sguinot, 1996; Klatzky, Beall, Loomis, Golledge, & Philbeck, 1999; Landau, Spelke, & Gleitman, 1984; Loomis et al., 1993; Müller & Wehner, 1988, 1994; Rieser, 1989; Rieser, Ashmead, Talor, & Youngquist, 1990; Rieser & Rider, 1991; Saint Paul, 1982; Wehner & Srinivasan, 1981). However, living in increasingly more complicated environments, humans seem to be faced with greater challenges to their navigation skills than other animals. Daily encountered human environments span miles and include both natural and artificial structures as well as subjectively imposed divisions among areas such as neighborhoods, cities, and states. Thus, these complex environments may require more complicated spatial representation systems.

Studies of human spatial memory have suggested that spatial knowledge is divided into a series of interconnected localized representations. The predominant view of memory for environmental layouts is that the individual representations of space are organized into a “hierarchical” structure in which representations

of smaller scale environments are stored at progressively lower levels (e.g., Hirtle & Jonides, 1985; Huttenlocher, Hedges, & Duncan, 1991; McNamara, 1986; Stevens & Coupe, 1978; Taylor & Tversky, 1992). For example, humans may maintain a system of individual representations for a city block, buildings on that block, offices in each building, and so on.

Although research has extensively examined the contents and structure of human spatial representations in memory, questions concerning the processes by which navigation is guided by more complicated representation systems (for example, a hierarchical system) are poorly understood. For example, navigation based on a system of separate representations can potentially increase cognitive economy by reducing the number of locations that must be processed at a given moment to only those that are most relevant. Such a system, however, may pose serious challenges to a navigator when he or she crosses (either physically, such as during navigation, or mentally, such as while plotting routes or directions) the boundaries that separate the representations we retain of the world. In this article, we present three experiments that explored the relationship between newly learned spatial relationships relative to existing spatial knowledge and the underlying processes that guide people from one environment to another.

Experiment 1

Experiment 1 examined the relationship between newly acquired spatial knowledge and the existing knowledge system. Subjects were confronted with a never-before-experienced, real-world environment that was nested within a larger, previously known space. That is, they came to our laboratory (a novel location) located within the confines of the University of Illinois campus. The question of interest was whether the new spatial knowledge about the laboratory (acquired through direct navigation) was built on the basis of, or linked to, the existing spatial knowledge system (i.e., the campus) to form a connected representational system.

Subjects were exposed to the location of several objects in the room after they arrived at the laboratory. Then they were blindfolded (to eliminate direct perception of the environments) and asked to indicate, by pointing, which direction would have to be

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traveled to arrive at a particular location within the room or on the campus. If subjects integrated a representation of the new environment in proper relationship to the old one, they should point to targets in the correct relationship relative to each other, regardless of the environment from which the target was selected. If subjects did not properly relate the new environment to the old, then direction judgments across the environments might not align.

Method

Subjects. Nine University of Illinois undergraduate students from an introductory psychology class participated for course credit. Subjects had attended the university for at least 1.5 years and were therefore very familiar with the campus. However, they were relatively unfamiliar with the psychology building (they had been attending classes there for less than 6 months) and had never been to the laboratory room.

Design and apparatus. Subjects were tested in a windowless rectangular room in the psychology building at the University of Illinois at Urbana-Champaign. The testing room and the campus served as the two probed environments. Five objects inside the room and five highly salient buildings on the campus served as targets for each environment (see

Figure 1, top). Targets were positioned (in the case of the room) or selected (in the case of the campus) so that subjects had to consider the 360° of space surrounding them. In a random order, subjects pointed to the various targets.

During an initial learning phase that allowed subjects to learn the locations of the room targets and during testing, subjects were seated in a swivel chair in the middle of the room. During data collection, subjects were blindfolded. An overhead video camera recorded their pointing responses. Each target was probed twice, yielding 20 trials per subject. Responses were coded from the videotape after completion of the experiment.

Procedure. Subjects came to the laboratory through either the north entrance or the west entrance of the psychology building (see Figure 2) by themselves. They then sat in the middle of the rectangular room surrounded by five target objects (see Figure 1, top left). The targets were pointed out to them along with their names, and the subjects were instructed to learn their locations in preparation for a spatial memory test. Subjects were permitted to examine the targets until they reported they were ready to continue. At this point, they were blindfolded and turned a small angle (less than 180°) to face a predetermined random direction. Thus, subjects could not produce accurate responses by pointing to the same region of space

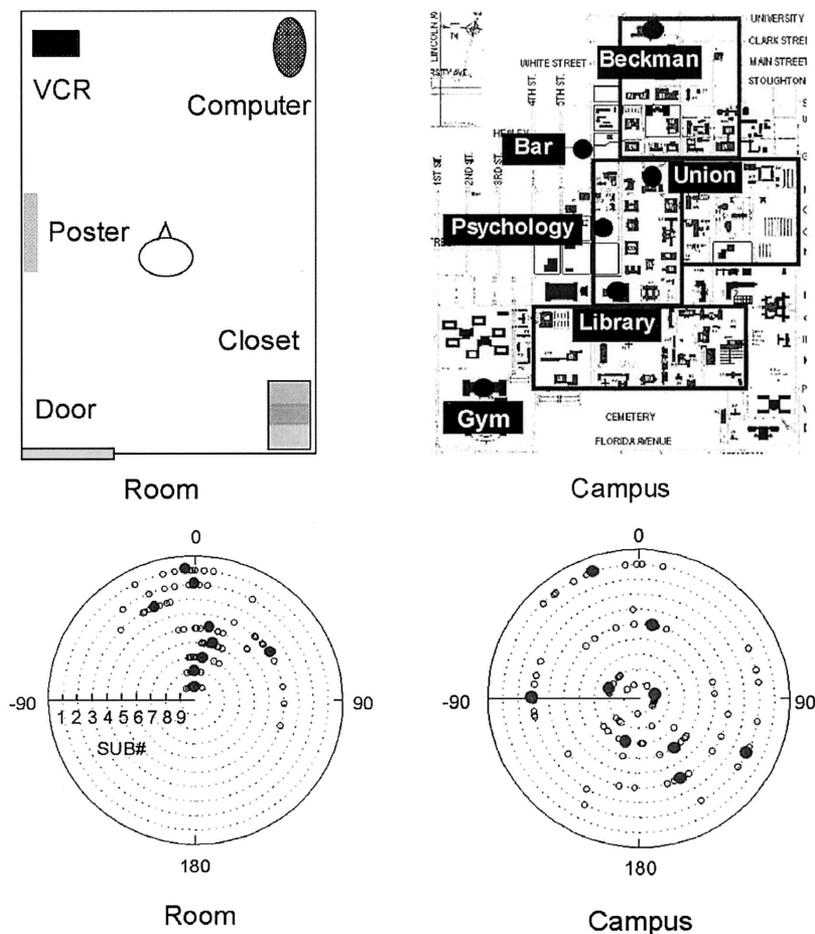


Figure 1. Top: The two environments used in Experiment 1 (the room and the campus). Bottom: The angular errors of each pointing response (pointing error) and the heading errors for each subject for the two environments. Each concentric circle represents one subject and each small open circle represents the pointing error for one response. The heading error for each subject is shown with a solid circle. SUB# = subject number.

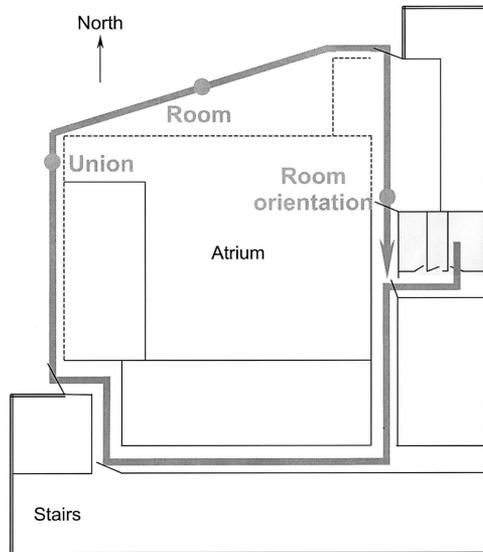


Figure 2. The environment and path for Experiment 2. The thick solid line shows the path of navigation. This path started in the testing room, proceeded outside the west entrance and around the building back to the main (north) entrance, and eventually led back to the room of origin. Circles represent the median response positions for the student union, the room, and the room's orientation. The thin solid line represents a solid interior wall; the dashed line represents a glass wall; and the thin solid double line represents a solid exterior wall.

relative to themselves that the target previously occupied. Subjects then pointed to the five room targets and five familiar campus buildings in a random order as the experimenter announced them, as accurately as possible with whichever hand was more convenient. Subjects were told that they were not under any speed stress and to respond as accurately as possible.

Data analysis. Two analyses of performance were conducted. The first analysis concerned whether subjects did indeed have accurate spatial knowledge of the two probed environments. This was addressed by examining the *configuration error* for each environment. The second analysis concerned whether subjects aligned the two environmental representations in correct relationship to each other. This was addressed by examining *heading error*. Both analyses were based on the method of Wang and Spelke (2000).

Both the configuration error and the heading error were calculated from the *individual error* associated with each target. Individual error indicates the mean angular error for each target, that is, the mean difference between the direction of the pointing responses to a particular target and the correct geographic direction of that target relative to the subject.

Configuration error was determined by calculating the standard deviation of the five individual errors for each environment. If the subject pointed to the five targets in perfect relationship relative to each other, the configuration error would be zero. The larger the configuration error, the more variable the individual errors, indicating the more inconsistent manner in which the subjects pointed to these targets relative to each other. Thus, configuration error indicates the accuracy of subjects' mental representation of an environment independent of their knowledge of their orientation relative to that environment. That is, if subjects misperceived the relationship between themselves and the target array as a whole, they would localize each target incorrectly with respect to geography; in theory, however, they could still show no configuration error if they pointed to each target in the correct relative relationship to the others.¹

Heading error was determined by calculating the mean of the individual errors across all targets within each environment. This is equivalent to the overall angular error of all targets in that environment. Similar heading errors with different environments would suggest that subjects had correct knowledge of the relationship between the two environments. Thus, heading errors should show the same type of distribution across subjects for the two environments if they are properly aligned. The clustering and randomness of the distributions were tested according to Batschelet (1981).²

Results and Discussion

All subjects spent less than 1 min learning the room targets. Configuration errors are shown in Table 1. The mean configuration error for the room was 9.6° ($SD = 6.8^\circ$). The mean configuration error for the campus targets was 32.3° ($SD = 17.6^\circ$), which was significantly larger than that of the room, $t(8) = 4.1$, $p < .01$. This difference between the two environments might have been due to a less accurate spatial representation of the campus or to degradation of spatial knowledge after disorientation (Wang & Spelke, 2000).³ The small configuration error for the room clearly demonstrated that the subjects effectively learned the room targets within a brief period. The key question of interest, therefore, involved the relationship between the heading errors for the two environments.

The heading error for each subject in each environment, along with the signed angular error (between -180° and 180°) for each pointing response, is illustrated in Figure 1. Pointing responses were coded in terms of their angular deviation from the true location of the probed target. Clockwise displacements were scored as positive, and counterclockwise displacements were scored as negative. As can be seen in Figure 1, the heading errors for the two environments exhibited quite different effects. Probing the room environment produced responses that formed a clustered distribution, $\chi^2(5, N = 9) = 34.3$, $p < .01$; within this distribution, the mean heading error across subjects was 16° . These results suggest that subjects maintained accurate knowledge of their orientation relative to the room targets. In contrast, the campus environment yielded a random distribution of responses, $\chi^2(5, N = 9) = 2.3$, $p = .80$, and the mean heading error was 98° . This result suggests that subjects greatly misaligned their representation of the campus with its actual spatial layout.

¹ For detailed discussions of the configuration error measure, see Wang and Spelke (2000). We made adjustments to the configuration error to correct for artifacts caused by testing subjects in a state of disorientation using a formula described by Wang and Spelke (2000, p. 227). Note that this calculation assumes that subjects had reasonably accurate perceptions of their position. The relatively small configuration errors for the room targets suggest that subjects perceived their position in the room correctly. Moreover, misperception of their position in the building did not change the target directions because of the large scale of the campus environment and therefore would not have affected the configuration error for campus targets.

² The circle was divided into six regions of 60° each. If the heading errors were randomly distributed, they should fall evenly in all six regions. A chi-square test was used to test the null hypothesis of random distribution (see also Wang & Spelke, 2000).

³ When subjects were tested while disoriented, configuration error could show an increase if they constantly changed their heading estimation from trial to trial or if the representation became inaccessible after disorientation (Wang & Spelke, 2000).

Table 1
Configuration Errors (in Degrees): Experiment 1

Location	Subject								
	1	2	3	4	5	6	7	8	9
Room	0.0	13.7	3.2	20.8	16.5	5.5	12.3	5.3	9.3
Campus	16.2	26.5	11.0	42.2	37.2	29.4	16.4	44.8	66.9

The preceding analysis shows that the heading errors for the room and campus environments were very different, indicating that subjects did not point to campus targets and room targets in correct relationship to each other. This suggests that subjects did not establish the link between the new environment and their existing knowledge of the campus, despite their direct navigation from campus to the room. As a result, even though they could orient themselves correctly within one environment, they misoriented themselves relative to another environment.

The failure to correctly establish directional links between different environments has important implications for navigation. What prevented subjects from establishing these links? That is, what processes were operating when subjects navigated between these apparently cognitively disconnected environments? To further investigate the dynamics of spatial representations during navigation between two apparently unlinked “units,” Experiments 2 and 3 measured subjects’ knowledge of their position relative to two environments during a direct navigation from one environment to another.

Experiment 2

The primary question of interest of Experiments 2 and 3 was how a multiple representation system guides navigation. That is, how is misalignment among representations resolved during navigation such that we do not continually experience a feeling of being disoriented or “lost”? Subjects in Experiment 2 navigated through space such that they entered or exited areas encoded in separate representations (i.e., the laboratory and the campus, which subjects in Experiment 1 could not integrate). The specific question addressed was what knowledge subjects have of their position relative to the environments in which they are not currently located (but from which they just came) and when changes in this information occur.

Method

Subjects. Fourteen undergraduate students drawn from the same population as in Experiment 1 participated in Experiment 2. None of the subjects in Experiment 2 had taken part in Experiment 1.

Design and apparatus. The environments used in Experiment 2 were the rectangular room used in Experiment 1, the psychology building, and the campus. Subjects walked along a prespecified path (see Figure 2) starting from the center of the room, turned to a hallway, and then, after a few right-angle turns along the hallway, exited the west entrance of the building onto the sidewalk of a street. The path then turned around the corner onto another street, rejoined the psychology building at the main (north) entrance, and led back to the room. While walking along this path, subjects were queried about the location of various targets both internal and external to the psychology building. Subjects indicated, again by pointing, the direction of these targets in relationship to themselves. Travel speed

was self-paced. Subjects were permitted to travel along the path until they were able to locate the target (i.e., they did not have to respond immediately on being queried).

Procedure. Subjects arrived at the laboratory on their own. All subjects entered the building immediately before coming to the laboratory. Thus, the environment navigated by subjects before their arrival was the campus.

Once in the laboratory, the subjects first learned the identities and locations of the five targets while sitting inside the room until they could point to the targets accurately with their eyes closed with pointing errors below 20°. Subjects then stood up and walked along the path, following the experimenter. At various locations (questioning positions), they were asked about their spatial relationship relative to various targets. If they could not immediately identify a target’s direction, they followed the experimenter along the path and then stopped and pointed to the target as soon as they were certain of its direction (response position).

The first target, the *student union* (a familiar campus target), was given at the path’s origin, and the experimenter immediately began to lead the subject down the path. Responses could be given at any point, even before movement began. Immediately on subjects’ response to the first target, the second target (the room from which they came) was given, and as before, the subjects walked until they provided a response. Thus, the response position of the first target (the student union) was the questioning position for the second target (the room), which differed for each subject. Finally, once they responded to the second target, subjects were shown a drawn layout of the room targets and asked to rotate the layout such that its orientation aligned with the actual geographic orientation of the room. Again, if a response could not be made immediately, subjects continued walking until they were able to offer a response. Although none of the subjects did so, note that all three responses could be given without ever leaving the room of origin. The experimenter recorded the response positions and the direction of responses on a map of the path. Subjects were told to not respond until they were sure of the accuracy of their response.

Data analysis. Data were analyzed according to two measures. First, accuracy of responses was determined by measuring the angular deviation of the responses from the correct direction. A response for a particular target was considered accurate if it fell within ±20° of the target’s true direction. Second, the positions on the path at which responses were given were recorded as indicators of when, in the course of navigation, the various targets could be addressed.

Results and Discussion

All subjects responded to all targets correctly. However, subjects showed clear alternation of awareness of their position relative to different environments during navigation. Median response positions for each target are illustrated in Figure 2 (55.1 m, 68.4 m, and 90.0 m from the starting point for the student union, the room,

⁴ The pointing direction was recorded on a map of the building, and the experimenter was trained to judge pointing directions within an accuracy criterion of 10°.

and room orientation, respectively). Almost every subject (93%) had to walk outside the room into the hallway to know the direction of the student union, a familiar campus location. By the time subjects became oriented to the campus, they had lost track of their orientation with respect to their origin; most subjects (80%) had to continue on their course to point to the room. Furthermore, even when subjects ultimately could indicate the general direction of the room, 87% could not orient a drawn layout of the room with respect to geographic direction and had to continue even farther along the path and back into the building.⁵

These results suggest two possible processes while subjects navigate between two cognitively separate environments. One possibility is that navigation between two environments involves a “map switching” process. According to this hypothesis, human navigation is a process that updates one’s position and orientation relative to a limited set of targets. Thus, navigators have to reorient themselves to an environment when approaching it and, at the same time, stop processing target locations in the environment they are exiting. Thus, reorientation occurs at particular spatial locations. A second possibility is that subjects required a certain amount of time to access their spatial knowledge and compute the direction of the new target. Thus, subjects had to walk further to respond to the next target not because they were at the “wrong” location but because they were engaged in a cognitive process that took time. Experiment 3 tested these possibilities.

Experiment 3

Method

The design of Experiment 3 was similar to that of Experiment 2, except for the following changes. Subjects were tested on only one target (the student union), and response time was recorded. Subjects started in the laboratory room and were led to the questioning position in the middle of the hallway at the southeast corner of the building on the ground floor. They were asked about the direction of the student union and then walked west along the hallway, went upstairs, and exited the west entrance to the sidewalk, if necessary, at different speeds until they provided a response. The experimenter marked their responses on a map and used a stopwatch to record the time it took them to respond. Thirteen new subjects from the same population were randomly assigned to the fast (6 subjects) or slow (7 subjects) group. The experimenter controlled walking speed by walking fast or slow in front of the subjects.

Results and Discussion

The question Experiment 3 sought to answer was whether subjects switched representations at given spatial locations or after a certain amount of time necessary for cognitive processing. If the distance between the questioning and response positions in Experiment 2 was a result of switching representations at particular spatial regions, then response time should have been faster for the fast group than the slow group, but distance traveled should have been the same. If the results of Experiment 2 were a function of time necessary to combine spatial knowledge to compute the new target direction, distance traveled should be significantly longer for the fast group, with response times being the same.

The results clearly supported the spatial location hypothesis. Mean walking speed was faster in the fast group than in the slow group ($M_s = 0.96$ m/s and 0.70 m/s, $SD_s = 0.08$ and 0.11 m/s, respectively), suggesting that the manipulation of walking speed

was effective. Importantly, mean response time was significantly shorter in the fast group than in the slow group (48.3 s and 67.3 s, respectively), $t(11) = 2.8$, $p = .02$, but there was no difference in mean distance traveled between the two groups (45.9 m and 46.5 m, respectively), $t(11) = 0.2$, $p = .88$. In addition, there was a high correlation between response time and walking speed ($r = .82$) but not between distance traveled and speed ($r = .12$). Thus, it appears that subjects had to reach a particular spatial region before they reoriented to the other environment, instead of needing a constant processing time.

General Discussion

In three experiments, we showed that humans readily form new spatial representations during navigation but do not necessarily incorporate them into the existing system of spatial knowledge. While navigating between these environments, people seem to switch representations to maintain on-line the environments they are approaching. Furthermore, this reorientation to new environments is accompanied by losing track of one’s position relative to the old environments. Such reorientation seems to occur at particular spatial regions instead of after a certain amount of time for cognitive processing.

Why did our subjects fail to integrate their spatial knowledge of the room with their existing knowledge of the campus, despite the direct link established by their continuous navigation between the two, and why did they switch between these representations during navigation? One possibility is that different reference frames are used to encode different environments. Various research has shown that multiple reference frames can be used to encode spatial locations and orientations (e.g., Carlson, 1999; Carlson-Radvansky & Irwin, 1994; Carlson-Radvansky & Jiang, 1998; Carlson-Radvansky & Logan, 1997; Franklin, Tversky, & Coon, 1992; Levinson, 1996; Mou & McNamara, 2002; Poucet, 1993; Shelton & McNamara, 2001). For example, McNamara and colleagues (Mou & McNamara, 2002; Shelton & McNamara, 2001) showed that judgment of relative direction among a set of objects was affected by the shape of the room in which these objects were housed, the mat on which the objects were placed, and the viewpoint of the observer. Thus, if target locations tend to be encoded in local reference frames, and if the human navigation system can track one’s position and orientation with respect to only one reference frame at a time, then it is not surprising that the subjects were not able to establish the spatial relationship between targets in one environment (encoded in one reference frame) and targets in another environment (encoded in a different reference frame) even after direct navigation between the two environments. It is also not surprising that people alternate their sense of orientation relative to different environments, when the navigation system changes reference frames and switches to the most relevant targets.

⁵ The subjects determined when they knew the direction of these targets. Different subjects might set different criteria. Alternatively, subjects could be asked to point to the targets along the path, and the pointing error would reflect their sense of direction relative to these environments. The current data suggest that errors decrease with distance (the mean error for the student union was about 90° in the room in Experiment 1 and was small [less than 20°] when the subjects were outside the building). Future research can examine pointing error as a function of distance.

A second possibility is that the human navigation system is fundamentally a dynamic, egocentric representation (Wang, 1999; Wang & Spelke, 2000). According to the dynamic egocentric representation hypothesis, humans navigate by establishing a set of target locations in the immediate environment and continuously computing the positions of these targets relative to themselves as they move, using various internal and external perceptual cues. Both fragmentation of spatial representations and constant switching are fundamental properties of a dynamic egocentric representation; because the representation is egocentric, the location and direction of all targets relative to the self will change constantly during navigation and thus need to be updated. An egocentric updating system may have intrinsic limitations in regard to the number of targets that can be “updated” at a given time (because on-line computations are costly) and the distance of the targets that can be updated accurately (because the farther the target, the less the egocentric vector will change as a result of one’s movements; Wang, 1999). Thus, targets have to be constantly dropped and reintroduced (e.g., reorientation) at given spatial locations where cues (e.g., certain landmarks) can be found to activate those representations. Such a system thus inevitably causes fragmentation in spatial knowledge if new knowledge is acquired when the old environment is dropped to make room for the newly learned environment.

These findings are generally consistent with hierarchical models of spatial representations in humans, in the sense that places are organized into “units” in the system. Subjects pointed to targets within the same environment in more or less correct relationship to each other even when they were incorrect about their own position and orientation relative to those targets. However, our results are inconsistent with traditional hierarchical models in which different representations are connected (Stevens & Coupe, 1978). In our navigation task, subjects failed to establish the directional link between different “units”; therefore, they constantly lost track of one environment when they reoriented themselves to the other one. More important, when asked to access their spatial relationship relative to a different environment, subjects did not need a given amount of time to combine two sets of spatial knowledge and figure out the relationship of a target in one representation to their position in a different representation (as proposed in some hierarchical systems); rather, they needed to arrive at particular spatial regions. Thus, spatial representations used in navigation appear to be independent of each other, and spatial relationships across different units of the representation system are often not easily computable.

These results do not suggest that spatial knowledge acquired during navigation is necessarily fragmented or that fragments of spatial knowledge can never be combined or integrated. Studies have shown that, under some conditions, new spatial knowledge is encoded in correct relationship to existing knowledge when common landmarks are available (e.g., Golledge, Ruggles, Pellegrino, & Gale, 1993; Montello & Pick, 1993). It is also easily conceivable that some levels of integration of spatial information will occur during repeated navigation, although sometimes the limitation can be quite profound (e.g., Brockmole & Wang, 2002; Moeser, 1988). It is also possible that the size of the fragments may differ between individuals, as a result of differences in working memory capacity or the use of other strategies. However, our studies suggest that this fragmentation may be the primary property of the human

spatial navigation system. Whether this property is unique to human navigation because of the increasingly complex environment or is a common theme in the entire animal kingdom remains an interesting question.

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