INTEGRATING KNOWLEDGE OF VERTICALLY ALIGNED LARGE-SCALE SPACES

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ABSTRACT: The acquisition and integration of configurational knowledge of spatial layout was studied in a large building complex containing several levels. Twenty-four college students learned two separate routes by walking around the complex; the two were located one above the other, although this was not visibly apparent. Subjects were then given a description that allowed them to integrate their knowledge of the two routes. Straight-line pointing errors and latencies revealed that subjects acquired considerable configurational knowledge about each route and about their relationship, although pointing was slower and less accurate between than within routes. The study demonstrates integration of separately learned spaces in a naturalistic setting, important to theories of environmental learning. It also provides data on learning in vertically aligned spaces and further evidence of the utility of self-report sense of direction as an individual-difference measure.

People acquire a great deal of knowledge about the spatial properties of large-scale environments (cities, buildings) in which they work and live, knowledge that supports sophisticated spatial behavior such as wayfinding and direction giving. The developmental course of this knowledge acquisition (*microgene-*

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sis) is complex and takes place over substantial time periods. At minimum, a distinction between three elements of spatial knowledge has been made (Chase & Chi, 1981; Siegel & White, 1975; Thorndyke & Hayes-Roth, 1982): landmarks, route knowledge, and survey or configurational knowledge. *Landmarks* are distinctive objects or places stored in memory that sometimes function in wayfinding and knowledge organization. *Route knowledge* consists of travel paths connecting landmarks. It is usually thought to contain information about endpoint landmarks and the order of turns but not necessarily metric information about distance and direction. *Survey knowledge* is the most maplike of the three. It consists of simultaneously accessible metric relational information about the locations of routes and landmarks in some part of the environment, organized within a common frame of reference. Because it is thought to include relational information about elements between which one has never directly traveled, the ability to take shortcuts, create efficient routes, or point directly between landmarks is taken as evidence for the existence of such configurational knowledge (e.g., Hardwick, McIntyre, & Pick, 1976; Landau, Spelke, & Gleitman, 1984).

An influential theory holds that a progression from landmarks to route knowledge to survey knowledge represents a microgenetic sequence in the learning of a new large-scale environment (e.g., Siegel & White, 1975). In particular, survey knowledge is thought to derive from accumulated route knowledge. Knowledge of routes that have been learned separately is said to be integrated or combined into more complex clusters or networks of routes

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(Hart & Moore, 1973; Moore, 1974; Siegel & White, 1975). When these "route clusters" are combined within a common frame of reference, survey representations result.

Only a small amount of research on the integration of route knowledge has been done, typically with small-scale simulations. Garfin and Pick (1981) had college students learn separate "routes" in tabletop arrays of objects by repeatedly reaching for locations while blindfolded. Subjects were then told that some of the locations overlapped and were asked to imagine the layout of the integrated arrays. Subjects then reproduced various distances: (a) within an array along a previously experienced route, (b) within an array but along a novel route (within-route inference), and (c) between the arrays along a novel route (between-route inference). Distances were reproduced equally accurately for the two within-route judgments, more accurately than for between-route inferences. Response times were equally slow for both types of inferences, however, slower than for judgments along previously experienced routes.

In a similar study, Hanley and Levine (1983) examined the integration of separately learned routes into more complex configurational knowledge using small schematic diagrams. Blindfolded subjects learned two diagrams via finger tracing; they were then given instructions about the spatial relationship of the diagrams that allowed the two to be integrated. Subjects demonstrated that they could integrate their knowledge by tracing shortcuts between points in the two diagrams with better than random accuracy. As in Garfin and Pick (1981), however, subjects were more accurate tracing shortcuts within a given diagram than between diagrams.

The acquisition of knowledge about *environmental* space has several properties (e.g., size and scale, sensory modalities involved, types of reference frames) that make generalization from small-scale spaces tenuous. Some research on the integration of separately learned environmental spaces has been done by Sullivan, Montello, Pick, and Somerville (1990). In one study, college students wearing a vision-restricting hood learned two simple pathways of several meters in length marked on the floor of a large room. They were then given a description that allowed them to integrate their knowledge of the two pathways, as evidenced by their ability to walk straight between pathway endpoints. As in previous work, within-path inferences were more accurate than between-path inferences. In a second study, Sullivan et al. had subjects learn the locations of several toys placed in two small sets of rooms on either side of a closed door. After being told that the other set of rooms was located through the connecting door, college students and 10-year-olds pointed straight to the toys, some within the rooms in which they were standing, the rest on the other side of the door in the second set of rooms. Again, within-room estimates were more accurate than between-room estimates. The study we report below further demonstrates the integration of separately learned naturalistic spaces, at an even larger scale than that previously used, and it examines additional aspects of configurational knowledge within and between separately learned spaces.

An important question involves the time course of configurational knowledge development. Several different models of this process have been suggested. Some have maintained that survey knowledge does not develop much from direct experience alone but requires exposure to maps (Moeser, 1988; Thorndyke & Hayes-Roth, 1982). Contrary to this, many studies suggest that some configurational knowledge is learned rapidly from travel alone, in as little as minutes or hours, although its accuracy and completeness may increase over the course of months or years (Gärling, Lindberg, & Mäntylä, 1983; Herman, Blomquist, & Klein, 1987; Herman, Kail, & Siegel, 1979; Kirasic, Allen, & Siegel, 1984; Kozlowski & Bryant, 1977; Lindberg & Gärling, 1981; Passini, 1984; Smyth & Kennedy, 1982). Still others have produced evidence that configurational knowledge develops simultaneously with route knowledge, at least for relatively simple routes (Foley & Cohen, 1984a; Hanley & Levine, 1983; Holding & Holding, 1989; Levine, Marchon, & Hanley, 1984), or even that clusters or networks of routes can be learned without first learning the routes separately (Moar & Carleton, 1982). The present study constitutes a further investigation of the time course of configurational knowledge development in a large-scale environment.

Most research on large-scale space has focused on two-dimensional layouts. This is probably adequate in many contexts. Buildings and areas within a city or neighborhood are distributed over a two-dimensional surface; elevation differences are important for effort and visibility, perhaps, but do not have implications for localization in most cases. However, localization in three-dimensional large-scale spaces would sometimes be important. Disorientation about one's location in a city is often reported by people leaving underground subways, for instance (e.g., Bronzaft, Dobrow, & O'Hanlon, 1976). Passini (1984) discusses the wayfinding difficulties engendered in multistory buildings and underground structures. The latter may be confusing not only because of the presence of a significant vertical component, and the lack of visual access between levels, but also because a sense of "enclosure" is difficult to acquire in a space that cannot be experienced from the outside.

There have been a few studies of orientation and wayfinding in three-dimensional large-scale spaces. Passini (1984) collected protocols from people wayfinding in multilevel shopping complexes. His subjects clearly needed knowledge about vertical relationships to make decisions about the use of stairways and elevators. Foley and Cohen (1984b) had students estimate distances between places on different floors of a five-story building. For parts of the building located more than one floor apart, a three-dimensional scaling solution fit the estimates better than did a two-dimensional solution. Several subjects reported three-dimensional modellike imagery for these parts of the building, rather than maplike or walklike imagery. Gärling, Böök, Lindberg, and Arce (1990) studied the existence of information about elevation in knowledge of city layout.

In an unpublished study on three-dimensional spaces by Lockman and Pick (discussed in Pick & Rieser, 1982), adults and children pointed to several targets within their two-story apartments. Within the same floor, the azimuths were quite accurate (about 15° error) for all subjects. And adults were just as accurate pointing to targets in the floor above or below them. However, the children, especially the youngest group, were less accurate pointing to targets located above or below. Similarly, the study we report below requires subjects to indicate straight-line directions (azimuths) to landmarks located on the level in which they are standing or in a level above or below them. Because part of one of the two routes is actually located on two different levels, the effects of elevation and route membership can be examined independently.

Also included is a simple measure of individual differences in large-scale spatial learning ability. Kozlowski and Bryant (1977) and Bryant (1982) asked subjects to rate their own "sense of direction" on simple 7- or 9-point scales. These ratings correlated rather strongly (around .5 or .6) with accuracy of pointing to nonvisible landmarks while imagining standing at various locations around campus. In one study (Kozlowski & Bryant, 1977), subjects' errors in pointing to the end after walking a mazelike tunnel were related to self-report sense of direction, but only after more than one learning trial. Such a measure was included in the present study, both to replicate it with an on-site orientation task and to check for its ability to predict route-integration ability.

In the present experiment, subjects learn two complex routes by walking in and around several buildings in a university health sciences area. One of the routes is located below the other, in hallways and tunnels entirely below ground level. Subjects learn the two routes separately in such a way that they are not aware of their mutual relationship in space. After learning the two routes, subjects are given information that allows them to integrate their knowledge of the two routes within a common frame of reference. During a final walk, subjects demonstrate their knowledge of the integrated spaces by pointing to several nonvisible landmarks on the route in which they are walking at the time and on the other route (above or below them). We expect that subjects will be able to point both within and between routes with better than random accuracy. However, we expect estimates made between routes to be slower (additional time required to access the integrated knowledge) and less accurate than estimates made within routes, as has been found with finger-traced routes.

METHOD

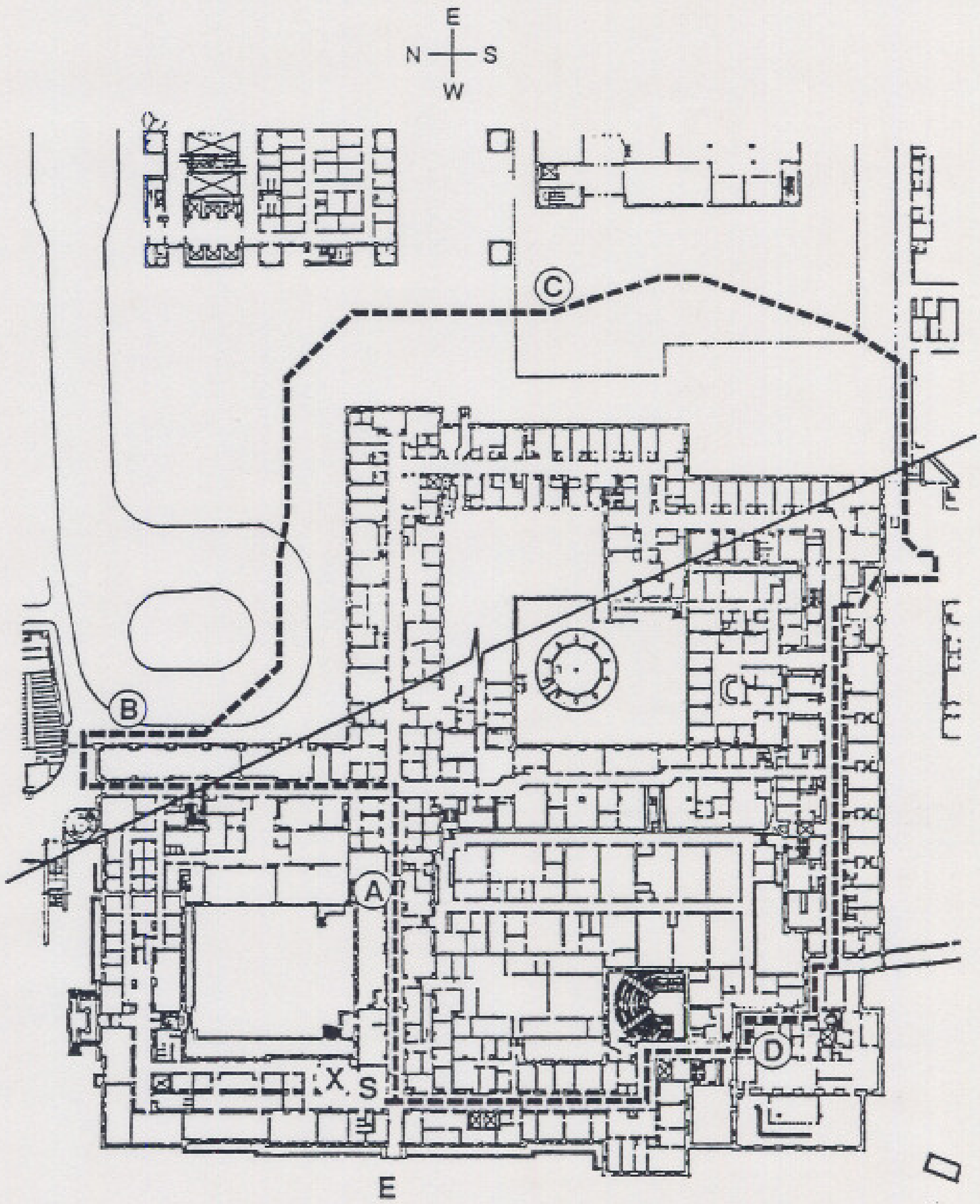
SUBJECTS

Subjects were 24 undergraduate and graduate university students participating in return for a $10 payment, 11 females and 13 males. Most subjects had been at the university for some time (4 to 120 months; median = 36 months), although prior familiarity with the health sciences complex was minimal. Median familiarity was 2 on a 7-point scale asking how well they knew the complex (1 = *not at all*, 7 = *perfectly well*), and no subject claimed greater prior familiarity than 5.

MATERIALS

Two experimental routes were used (Figure 1), located in and around the complex of Health Sciences buildings on the campus of the University of Minnesota. The top route was located above ground and above the bottom route, which was located below ground (the actual vertical relationship between the two is depicted in Figure 2). Nearly half of the top route went outside of the buildings; the bottom route was entirely underground and wound around basement hallways and tunnels. The top route was on two levels, the level change being shown by a straight line through the middle of the top route in Figure 1. The inside portion of the top route (below the straight line) was one level above the bottom route; the outside portion was two levels above the bottom route. The two routes differed in shape, although both contained 15 to 20 turns and were closed loops that did not cross over themselves at any point (*tori* or topological "doughnuts"). The top route was about 500 m in length; the bottom route was about 530 m.

Subjects began learning each route at starting points (*S* in Figures 1 and 2) located one exactly above the other, although subjects did not initially know that. A tunnel (*T* in Figure 1) that goes across the street to the neighboring student health center was used to walk between the two starting points during the learning phase of the experiment. This was intended to keep



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subjects from realizing that the two routes were actually above one another before they received the integration instructions. In fact, 19 of the 24 subjects reported having had no idea of the vertical relationship of the two routes before receiving the integration instructions, and the other 5 reported only imprecise,

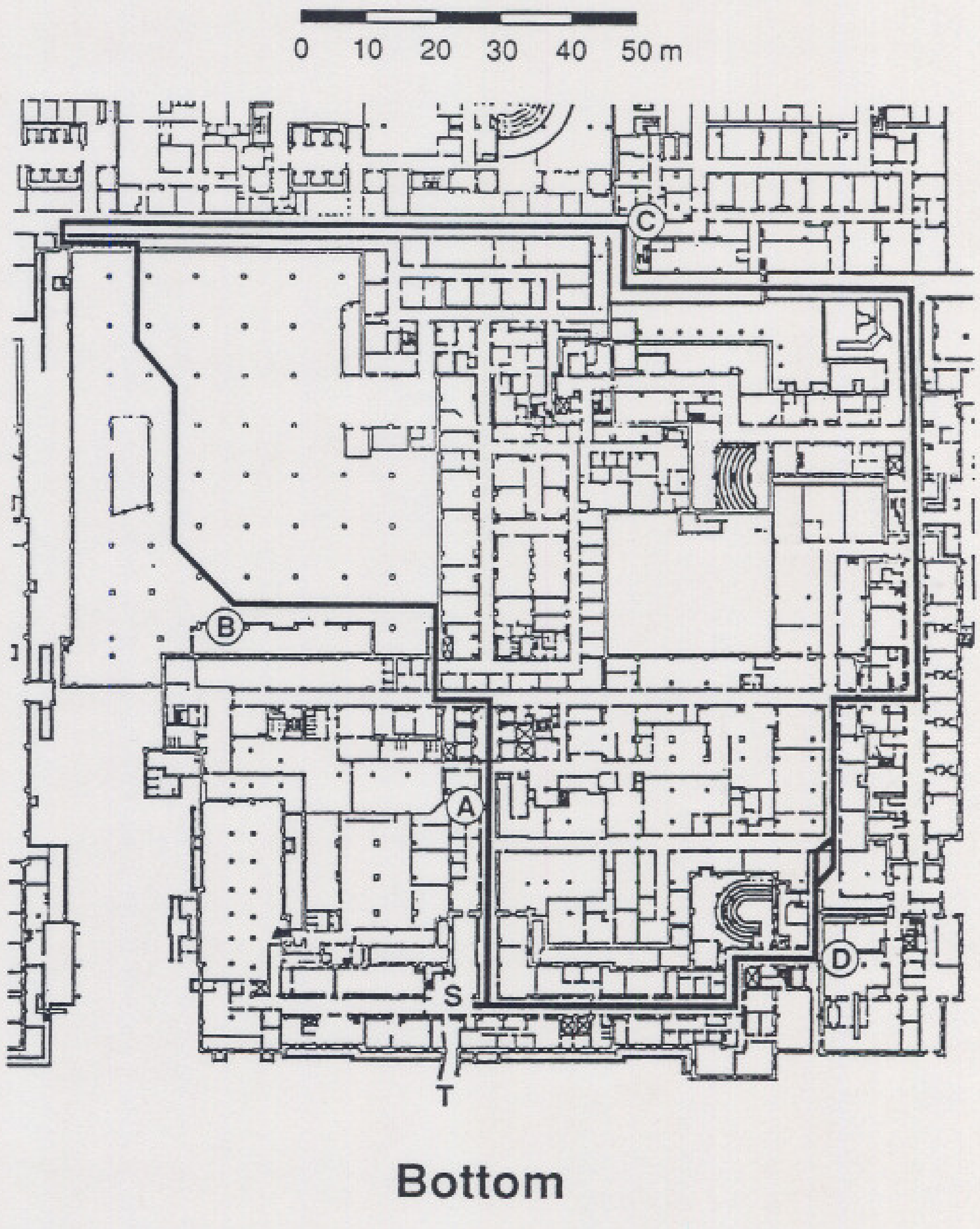

Figure 1: Test Routes In and Around Health Sciences Complex
NOTE: Dashed line is top route, solid line is bottom route. E = entrance to top route, T = tunnel to bottom route, S = starting locations, X = stairs used in condition VD, circled A through D = landmarks. Straight line through middle of top route indicates a change of levels and a change from inside to outside the building (outside and highest level above line, inside and middle level below).

uncertain knowledge of this. A stairway (*X* in Figure 1) was used in one condition to give subjects direct information about the vertical relationship of the two routes.

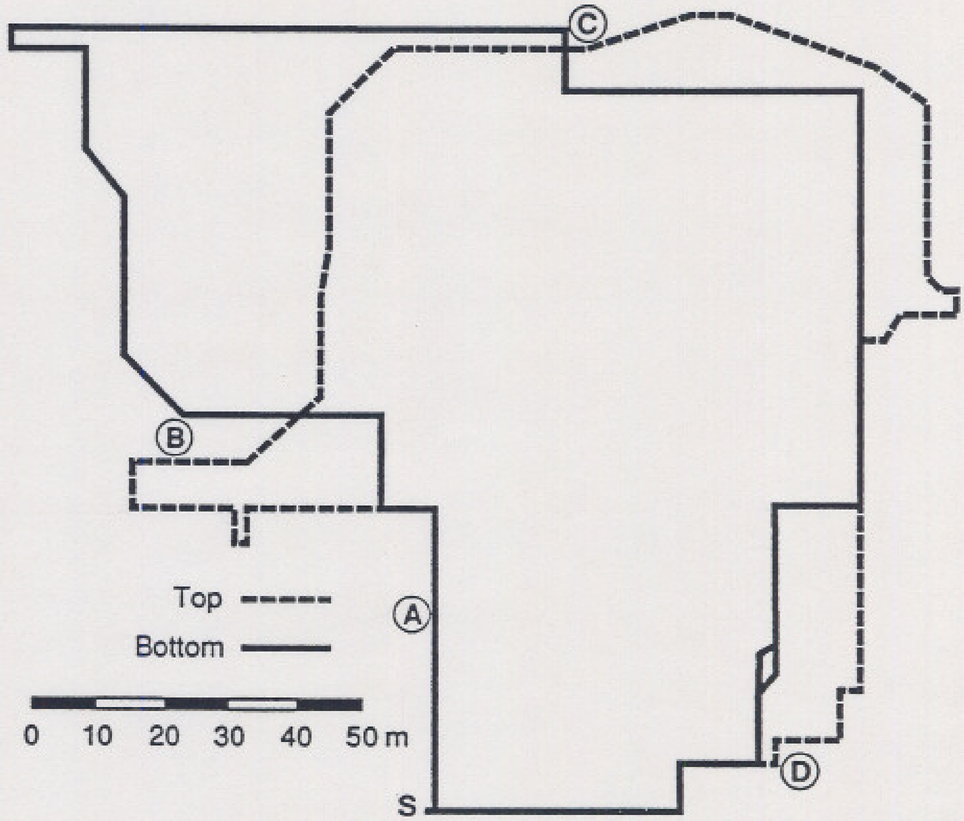

Figure 2: Integrated Test Routes
NOTE: S = starting locations, circled A through D = landmarks.

Performance was assessed in relation to four pairs of vertically coincident test landmarks, one member of each pair being located on each route (*A* to *D* in Figures 1 and 2). Landmarks on the top route were: A_t (frosted window), B_t (bus stop sign), C_t (turquoise monument), and D_t (lockers). Their counterparts on the bottom route were: A_b (glass sculpture), B_b (high-voltage door), C_b (Diehl-hall sign), and D_b (rectangular mirror). These landmarks were chosen and labeled as such for several reasons. They were visually separated from each other and spaced fairly evenly around the routes, with clear point locations and memorable names. Coincident pairs of landmarks were used so that differences in pointing to the landmarks within versus between routes could not be attributed to differences in the distances and directions of those landmarks from subjects' pointing locations.

A circular pointing device was used to collect directional estimates. It was 28 cm in diameter with a drawn radius line and a pointing wire that could be rotated on one side. The back side had degree markings from which the experimenter read subjects' directional estimates. A stopwatch was used to collect response latencies. Subjects drew a sketch map of the two routes on a blank, 8 ½ × 11 inch (21.6 × 27.9 cm) sheet of paper.

PROCEDURE

Subjects were tested individually. The procedure consisted of three phases: *learning*, *integration*, and *testing*. The subject and experimenter walked to the starting point in the top or bottom route (counterbalanced), entering the tunnel across the street to get to the bottom route. Subjects stood at start, facing north and the experimenter. They were told that we were studying spatial learning in large spaces, and that we would take a walk around the area together. They were told to pay attention to and memorize the names and locations of several landmarks we would stop at. Half of the subjects first walked in the clockwise direction, and the other half walked counterclockwise; all subjects walked their second route in the opposite direction.

On coming to the first landmark, the experimenter stopped and stated its name twice. After 3 to 5 seconds, walking resumed in the same direction. Stopping and naming was carried out at each landmark, and the names of all previously learned landmarks in that route were repeated as each new landmark was learned.

After walking the route once, subjects were told they would walk it again to make sure they had learned the names and locations. Before resuming, subjects were asked to name the first landmark on the route and to estimate how far they would walk to get there (verbal estimate in any units they wished). Errors in landmark recall were noted and corrected (in fact, only five subjects erred even once on landmark recall during the study). Distance estimates were requested only to induce subjects to think carefully about the spatial properties of the route during the learning phase without focusing them directly on the configurational knowledge that would be asked about later. Therefore, learning of the separate routes was not strictly incidental (as it might be under natural conditions), but we thought it was essential for the separate routes to be well learned before integration could be done successfully. Distance estimates are not discussed further below.

After completing the second walk, subjects were asked to name the landmarks in the order they had learned them. Again, any mistakes in name recall were noted and corrected. Subjects were then taken to the starting point of the *other* route via the neighboring tunnel. They were told that they would learn a new route with new landmarks but not to forget the route they had already learned because they would later be asked about it. The learning procedure used with the first route was then repeated with the second route. No reference to the first route was made during the learning of the second route.

After learning the second route, subjects were asked to recall the names of the four landmarks in the first route they had learned. Then the integration phase was carried out. An equal number of subjects received the integration instructions in one of three ways: (a) V1 = verbal instructions from the first start, (b) V2 = verbal instructions from the second start, or (c) VD = verbal instructions plus direct exposure from the second start. Subjects in condition V1 walked back to the first start via the neighboring tunnel before receiving the integration instructions. Subjects in condition V2 received the instructions from the second start where they already were standing; comparison of V1 and V2 allows detection of primacy or recency effects. Subjects in condition VD also received instructions from the second start; in addition, they directly experienced the relative locations of the two starts described in the instructions (one directly above the other) by walking from the second start to the first, and back, via the stairway about 7 m away (*X* in Figure 1). Condition VD was included to find out if direct exposure to the two routes would improve comprehension of their relationship. Thus half of the subjects were tested from the top route and half from the bottom; two thirds of the subjects were tested from the second route they had learned.

All subjects received the following integration instructions while facing north at one of the two starting points:

> It turns out that the two routes you learned today are actually located roughly one above the other. The starting point we are now standing at is directly (below/above) the starting point from the other route. Furthermore, the direction you are now facing is north, just as the direction you faced at the other starting point was north. Think about this for a moment. Can you imagine where the other route and all the landmarks are located from where you are now?

The instructions were repeated several times if necessary (as many as three times), until subjects claimed to understand the relationship of the two routes.

The testing phase was then conducted. Subjects took one more walk around the route in which they were standing, in the direction they had learned that route. They were told to keep the relationship of the two routes in mind. At each landmark, they stopped and faced north (they were not told which direction they were facing at the landmarks). The experimenter held the pointer in front of subjects, with the drawn radius and pointing wire facing directly toward them. Its use was explained and demonstrated. Subjects were asked to "point straight to the various landmarks" and to "just indicate the 2-dimensional direction, ignoring any differences in vertical height" (i.e., to indicate azimuth only). They were to point as soon as they thought they knew where a specified target landmark was, to make sure they made their best guess without wasting any time. The stopwatch was started when the name of a test landmark was stated; it was stopped when subjects took their hand away from the pointer. Pointing latency and direction were recorded, the pointer was reset to the initial position, and the next landmark was stated. All seven landmarks other than the one at which subjects were standing, including one directly above or below, were pointed to in different randomized orders for each subject. This was repeated at the remaining three landmarks on that route, with different random orders at each place, resulting in a total of 28 pointing responses from each subject.

After returning to start, subjects drew a sketch map of the integrated routes as accurately as they could. After completing the maps, they answered questions about the length of time they had been at the university and rated their previous knowledge of the health sciences complex. Finally, subjects estimated the percentage of adults who had a better sense of direction than they did. An experimental session lasted between 70 and 90 minutes.

RESULTS

The multivariate approach to repeated measures was used to analyze mean pointing deviation (mean absolute value of error from correct) and latency in several mixed-model ANOVAs.[1] Initial analyses involved two repeated factors: within-route versus between-route responses, and the four stationpoints from which responses were made (one member of each of the four pairs of vertically coincident landmarks, A, B, C, and D). Walking direction (clockwise on top vs. clockwise on bottom) and integration condition (V1, V2, VD) served as between-subjects factors. Responses to the target landmarks actually located directly above or below the stationpoint were excluded from the main analyses. A small number of responses (4.5%) in which subjects incorrectly stated that the target landmark was directly above or below where they were standing were scored as 90° (chance, given a possible range of 0 to 180° error).

As hypothesized, pointing error (Figure 3) was significantly greater between (59.9°) than within routes (32.7°), $F(1, 18) = 42.35$, $p < .0001$. However, both were significantly less than chance error of 90°, indicating some configurational learning within routes and some integration between routes. Error also differed as a function of stationpoint landmark, $F(3, 16) = 16.98$, $p < .0001$. Figure 3 indicates that error was not equal at all landmark pairs, although a nonsignificant interaction of landmark pairs by within-between routes, $F(3, 16) = 0.37$, suggests that the within-between difference in error was replicated at each landmark pair. Notably, pointing error did not differ as a function of integration condition, $F(2, 18) = 1.93$, nor of the interaction of condition by within-between routes, $F(2, 18) = 1.22$. In other words, the place and manner in which subjects learned about the relationship of the two routes did not influence the accuracy of their integrated knowledge. No other main effects or interactions were significant at the .05 level.

A similar analysis of latency (Figure 4) revealed that it also differed as a function of whether subjects pointed within or between routes, $F(1, 18) = 12.60$, $p < .005$. Subjects were faster within routes (7.0 s) than between routes (8.5 s). However, this difference interacted with the stationpoint landmark from which data were collected and the direction in which subjects walked the two routes (three-way interaction $F[3, 16] = 4.84$, $p < .05$). Simple effects tests revealed that the within-between route difference did not significantly interact for subjects who walked the top in the counterclockwise direction, $F(3, 16) = 0.25$. In this case, the within-between route difference was significant at the .01 level, $F(1, 18) = 9.70$. The within-between difference did interact with stationpoint for subjects who walked the top in the clockwise direction, $F(3, 16) = 8.03$; the within-between difference was significant at all four stationpoint landmarks except *C* (Fs[1, 18] = 6.98, 17.38, 0.00, 4.58, respectively). For the most part, therefore, latency patterns revealed the predicted difference of within route being faster than between route. Besides these effects, no other main effects or interactions involving latency were significant at the .05 level.

Additional analyses examined several other between-subjects factors that may have influenced pointing. Each factor was analyzed in a separate mixed-model ANOVA that included integration condition (V1, V2, VD) and the two repeated-measures factors described above (within-between route, stationpoint). These factors were the route from which data were collected (top or bottom), the order in which routes were learned (top or bottom first), and subject sex. None of the main effects or interactions in these analyses reached significance at the .05 level, for either latency or pointing error.

Two comparisons were made to establish whether elevation differences could account for the within-between route differ-

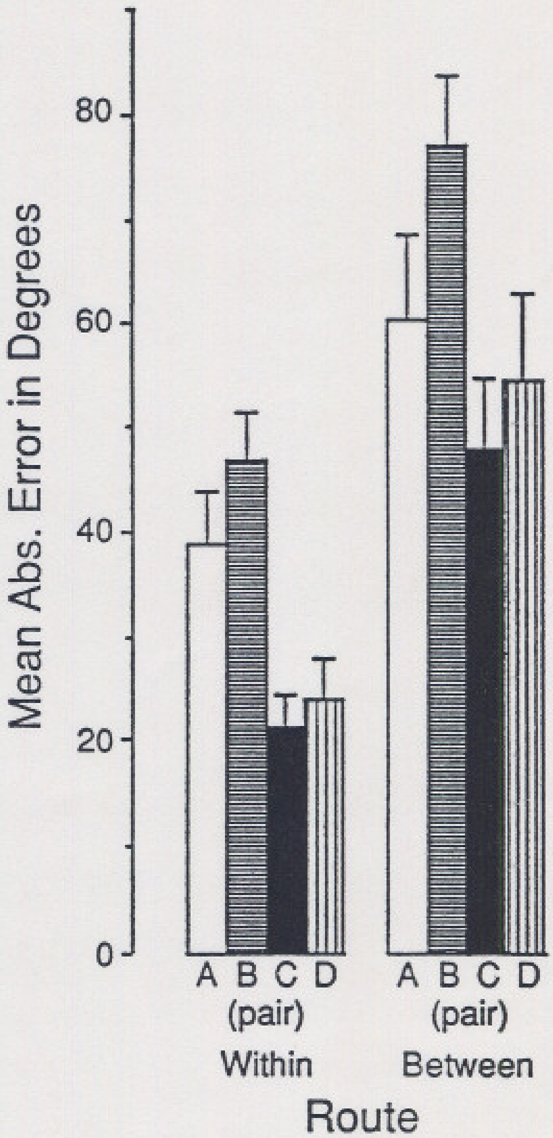

Figure 3: Mean Error In Pointing From the Four Landmark Pairs, Within Route and Between Route, With Standard Error Bars

ences in accuracy and speed. These comparisons took advantage of the fact that the top route was actually located on two different levels (top landmarks A and D one level above the bottom route, B and C two levels above—see Figure 1). The first comparison contrasted a subset of the within-route judgments (from A and D to B and C, and vice versa) in the top and bottom routes. These judgments went across levels in the top route but

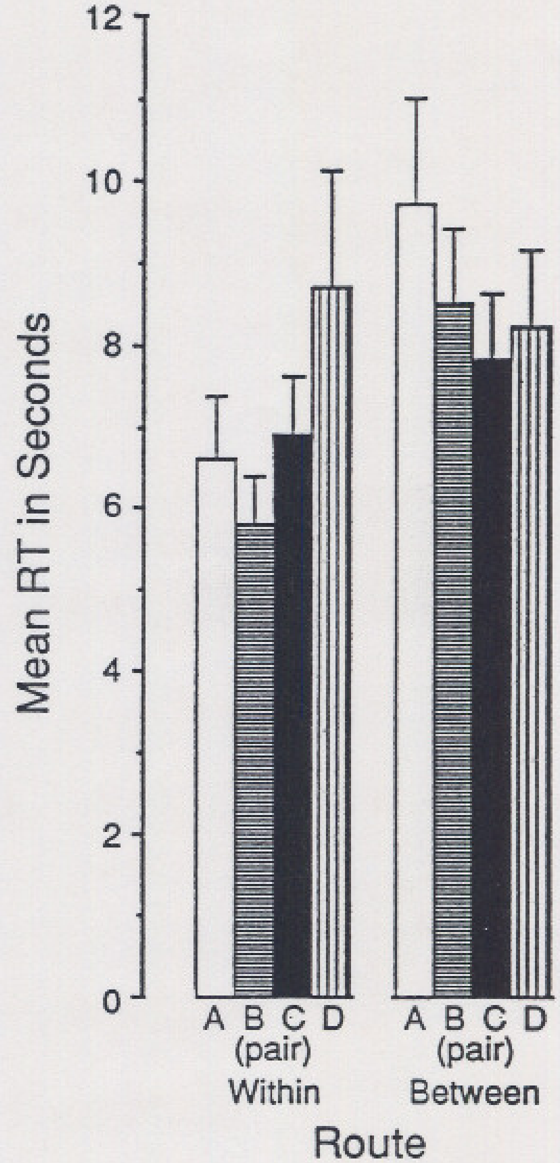

Figure 4: Mean Response Time (RT) In Pointing From the Four Landmark Pairs, Within Route and Between Route, With Standard Error Bars

were all within the lowest level in the bottom route. Responses to these within-route judgments were equally fast and accurate in the top as in the bottom, $Fs(1, 22) < 1.0$, indicating no effect of elevation differences on within-top judgments. The second comparison contrasted two subsets of within- and between-route judgments made from the top route only. Both involved stationpoint and target landmarks differing by one level in elevation (from A and D top to B and C top, or A and D top to B and C bottom). In this case, the within-between differences in accuracy, $F(1, 11) = 11.75$, $p < .01$, and in latency, $F(1, 11) = 7.38$, $p < .05$, were still found. Taken together, these two comparisons show that within-between route differences in performance were not due to elevation differences.

Responses to the target landmarks actually located directly above or below where the subject was standing were excluded from the main analyses reported above. Out of 24 subjects, 8 correctly stated this relationship on one or more trials (only 2 subjects correctly stated this on all four opportunities), for a total of 17% of such trials. Analysis of latencies revealed that subjects were no faster or slower in responding to these coincident landmarks than to the other landmarks, nor did latencies to these landmarks depend on any of the other variables in the study.

Finally, a significant correlation between pointing error and latency, $r(22) = .50$, $p < .05$, indicated that there was no speed-accuracy trade-off. Rather, as suggested by the parallelism of results in the above analyses, error and latency reflected a common performance difficulty in this experiment. However, the correlation between differences in error, and in latency, within versus between routes was small and nonsignificant ($r = .20$).

SKETCH MAPS

Subjects' sketch maps were examined for further evidence that they had learned the landmarks and two routes, and had understood and completed the integration task successfully. Although it is true that poor sketch maps are questionable as evidence of poor performance, successful sketch maps do provide relatively sound evidence of good performance. The maps were examined with respect to several topological and ordinal characteristics; they were not considered useful as evidence of metric knowledge. Out of 24 subjects, 79% had all eight landmarks in the correct order, the remaining subjects reversing the order in one route or the other. Only 54% of subjects drew the two routes as being nearly equal in size, which in fact they were. The top was not consistently depicted as being larger or smaller than the bottom, even though it went both inside and outside of buildings (six subjects showed the top as being considerably larger, five showed the bottom as being larger). Seventy-nine percent of subjects drew the two routes as being considerably different in shape from each other, which was also true. Seventy-one percent of subjects correctly drew the corners of the two routes at the start locations as being overlapping and perfectly coincident; the rest drew these corners as being shifted or contracted in some way. On the average, 13.3 turns were drawn in the top route and 12.0 in the bottom route (both contained about 17); the range of turns depicted was around 20 in both cases. Nearly all subjects correctly drew the two routes as being single-closed loops or tori, only two subjects showing one of the routes as a figure "8".

It is possible that within-between pointing differences were caused by a subset of subjects who simply did not understand the integration description of the relative positions of the two routes. To investigate this possibility, analyses were repeated on only those subjects who integrated the routes correctly in a topological sense. These were the 14 subjects whose sketch maps indicated that they had (a) ordered the landmarks correctly in the two routes, (b) aligned the corners of the routes at the start locations correctly, and (c) depicted the routes correctly as two overlapping doughnut shapes. Even given this small sample size, the results of these analyses were almost identical to those based on all subjects. In particular, pointing error was greater between (58°) than within routes (35°), $F(1, 8) = 22.40$, $p < .001$. Unlike the overall analysis, however, error from subjects drawing correctly integrated maps did differ as a function of integration condition, $F(2, 8) = 6.39$, $p < .05$, but the very small and uneven group sizes for this between-subjects comparison suggests caution in concluding anything from this. Latency effects in these 14 subjects were also very similar in magnitude to those of the entire sample. In particular, latency was greater between (8.2 s) than within routes (6.8 s), $F(1, 8) = 9.48$, $p < .05$.

SELF-REPORT FAMILIARITY AND SENSE OF DIRECTION

Neither length of attendance at the university nor degree of prior familiarity were significantly related to pointing error or latency (all r^2s < .03). Nor were they significantly related to the size of the difference in error within and between routes. However, both increased length of attendance ($r[22] = -.52$, $p < .01$) and increased prior familiarity ($r[22] = -.54$, $p < .01$) were fairly strongly associated with a decreased difference in pointing latency within and between routes. Subjects who had attended the university longer and knew the test buildings better prior to the study tended to point between as compared to within routes in more nearly the same time. Attendance and familiarity correlated .67 with each other.

As found previously by Bryant and colleagues, however, self-report sense of direction ("What percentage of adults has a better sense of direction than you?") correlated fairly strongly with both pointing error and latency: .41 with error ($p < .05$) and .52 with latency ($p < .01$). These indicate that subjects reporting a better "sense of direction" were faster and more accurate. Within-between difference in error was correlated .29 with sense of direction, but this did not reach statistical significance with 24 subjects. Difference in latency was nearly perfectly uncorrelated (–.01) with sense of direction.

CASE STUDY EXAMPLE

It is informative to examine in detail the performance of a single subject who did exceptionally well. She learned the top route first, walking in the counterclockwise direction, and received verbal integration instructions from the bottom route. Thus her pointing responses were collected from the bottom route. This subject had only been at the university for 4 months at the time of testing and claimed that she did not know the health sciences area at all prior to the study. Given this lack of prior familiarity and the high quality of her performance described below, she may have been too generous when she

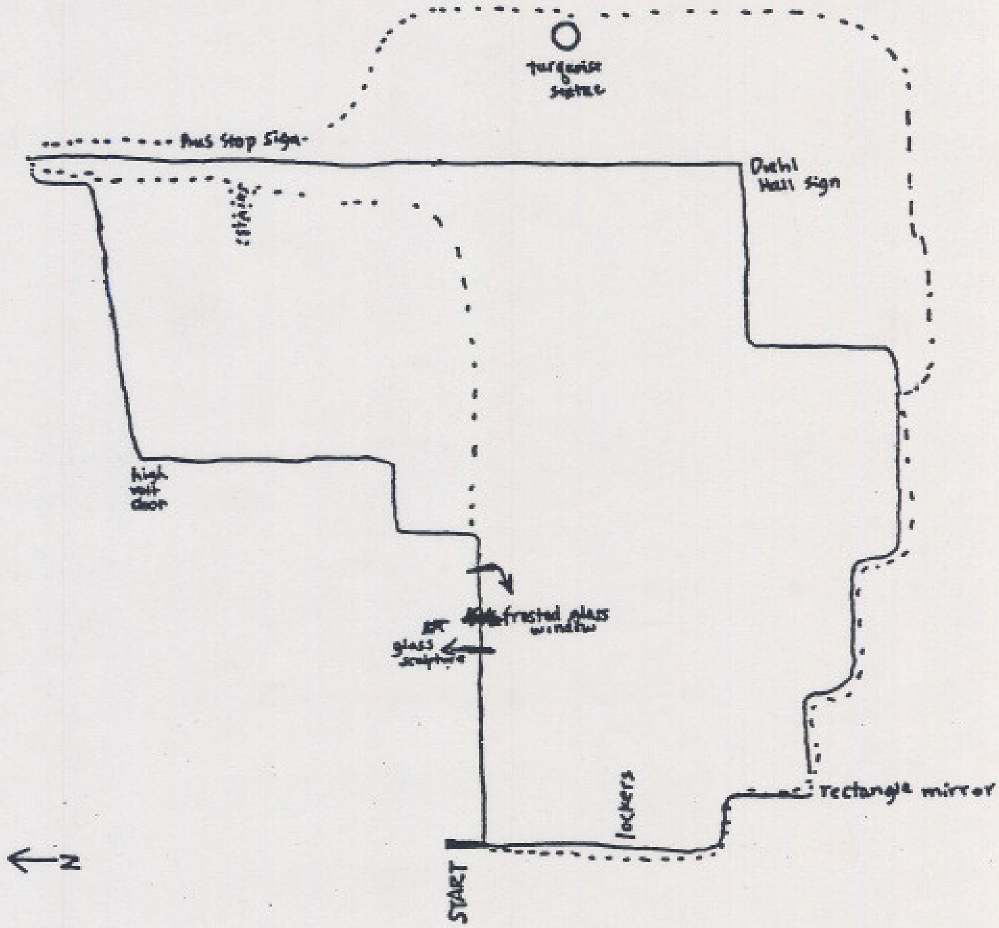

Figure 5: Sketch Map Drawn By Case Study Subject

reported that 15% of the adult population has a better sense of direction than she has.

She was among the most accurate subjects at pointing within the bottom route (mean error = 14°). And despite not realizing that the two routes or the start locations were above one another until receiving the integration instructions, she was only a little less accurate pointing between the routes to the top landmarks (mean error = 23°). She was also quick at pointing, both within (4.8 s) and between (5.8 s) routes. One can see by comparing her sketch map in Figure 5 to the actual integrated routes in

Figure 2 that she in fact learned the configurational layout of the two routes remarkably well. This is especially notable considering the size and complexity of the routes and the fact that she spent less than 1 hour walking them. This subject surely displayed some of the complex and sophisticated large-scale spatial learning that is possible for humans, even when they never see a map of the environment.

DISCUSSION

Essentially naive subjects in this study acquired configurational knowledge of two large-scale routes in a hospital complex, given only about 30 minutes to walk around each route. This is supported by the fact that subjects were able to point straight to landmarks located along the routes fairly accurately without direct visual access and could draw sketch maps with better than random accuracy. Furthermore, subjects integrated separately learned routes into a common frame of reference, an important step in theories of large-scale spatial learning. Given a verbal description of the relationship between the two routes, subjects walking along one route were able to point with better than random accuracy straight to landmarks located along the other route. This was true in spite of the fact that subjects were generally quite unaware of the relationship of the two routes in space before they received the integration instructions. And there was no difference in the ability to demonstrate knowledge of the integrated routes as a function of which route (top or bottom) subjects pointed from, essentially a replication of the finding.

However, performance was clearly impaired when pointing from one route to the other as compared to pointing within a route. Error and latency were about 30° and 1.5 s greater pointing between than within routes. Four possible explanations were shown to be unable to account for the difference. It cannot be due to differential direction or distance to the landmarks in the two routes, as in some previous research, given that target landmarks in each route were matched (pairs of vertically coincident landmarks). Nor can it be due to recency of learning: Whether subjects received the integration instructions and performed the pointing tasks from the first or second route they had learned did not influence the within-between route difference. Also, elevation differences between the two routes cannot account for the within-between difference. The top route itself contained landmarks at two different levels. Pointing did not differ within the top route as a function of elevation, and the within-between route difference persisted even when the within-route judgments included only those involving landmarks at different levels. Finally, our results suggest that the within-between differences were not caused by some subjects simply failing to understand or carry out the integration of the two routes. Between-route pointing was reliably better than chance. And even when performance was examined only for subjects who integrated the two routes topologically correctly on their sketch maps, the within-between difference remained statistically reliable and nearly identical in magnitude.

We can explain the within-between route differences in pointing by considering the knowledge structures and processing mechanisms involved in indicating directions to nonvisible landmarks or locales. The task requires a coordination of perceptual information about one's location with knowledge of part of the environment stored in memory. Pointing to landmarks within a route requires people to recognize the place where they are located, access configurational knowledge of the route that includes the location of the target, "extract" the straight-line direction between their current location and the landmark in question (perhaps through image scanning), and translate this direction into a response. Alternatively, people could carry out a more or less continuous updating of their location within the routes as they walk along; only that part of the process involving the particular target landmark would need to be carried out after the question was posed. This alternative may place an unrealistic demand on processing capacity, but either way, the implications are similar. Spatial behavior involving configurational knowledge could thus be in error for several reasons: mistaken identification of one's location, inaccurate stored knowledge, inaccurate manipulation of knowledge in working memory, or inaccurate translation of the direction into a behavioral response.

The same processes would be required to point to landmarks on another route, one through which the person is not walking. But in this case, people would need to activate integrated knowledge of the two routes, not just of the route through which they are walking. Integrated knowledge could be retrieved from long-term memory or it could be repeatedly constructed in working memory from separate knowledge of the two routes and their relationship. In either case, knowledge about the relationship of the two routes would contain some error over and above that in the separate representations, and would probably require additional processing time. In short, acquiring configurational knowledge of the relationship of separately learned spaces is a distinct and developmentally more advanced process than acquiring configurational knowledge of a single space learned as part of a unitary travel experience.

This explanation expands on Hanley and Levine's (1983) account. They proposed that knowledge of the separate routes is more well learned, or better remembered, than is knowledge of the relationship between the routes in the integrated representation. In support of this, they found that between judgments were no slower or less accurate than within judgments when memory for both the separate routes and the integrated routes was rated as either very high or very low. By implication, integrated representations will eventually become well learned, and configurational knowledge will be just as quickly and accurately accessed between the originally separate routes as within them. An important question is whether "incubation" time alone will induce complete integration of knowledge or whether specific forms of practice are necessary.

Subjects did not seem to integrate the routes any better if they were allowed to directly see the relationship of the two via the stairs nearby (condition VD) in addition to receiving a verbal description. Like large-scale spatial learning in general, information about the relationships of separately learned parts of the environment normally comes from one of three sources, the first two of which were used in this study: verbal descriptions, direct experiences while traveling, and maps. More research needs to be done comparing the relative qualities of these sources (e.g., Thorndyke & Hayes-Roth, 1982).

The present study also demonstrates large-scale spatial learning in three-dimensional or "vertical" environments. Subjects were able to construct and access integrated representations of spaces located at different levels, one above the other. Such knowledge might be useful in environments such as high-rise buildings and underground spaces. Future research should further address the nature of wayfinding and representational difficulties in environments where elevation or location along a dimension of height is important, especially considering the continued importance of multilevel built environments, both above and below ground.

A simple self-report estimate of sense of direction correlated fairly strongly with pointing performance, replicating and extending Kozlowski and Bryant (1977) and Bryant (1982). However, the degree to which subjects formed an integrated representation of the two spaces (as reflected in differential accuracy and speed within vs. between routes) was not related to sense of direction. This may reflect subjects' positions in a learning curve. Subjects with "good" sense of direction in one of Kozlowski and Bryant's (1977) studies did no better than subjects with "poor" sense of direction on their first learning trial; error was less for the good subjects only after more trials. Our data did reveal a relationship between overall performance and sense of direction, but subjects had walked each route twice. Perhaps additional learning and development of the integrated representation would have revealed a relationship between sense of direction and within-between response differences. In any case, the lack of such a relationship argues against the idea that self-report sense of direction merely reflects subjects' self-assessments of how they had done on a preceding task (as suggested by Passini, 1984).

The present study adds to the modest body of research on wayfinding and spatial learning in naturalistic contexts such as buildings and cities (e.g., Evans, Fellows, Zorn, & Doty, 1980;

Evans, Marrero, & Butler, 1981; Peponis, Zimring, & Choi, 1990). Given the size and complexity of the routes used in this study, and the limited amount of exploration allowed, the task required of our subjects probably taxed the limits of their skills at large-scale spatial learning. Nearly all subjects commented that they had found it to be very demanding, a few stating that they were quite disoriented and were answering with very little confidence in their knowledge. As a controlled investigation of such a difficult task carried out in situ, research similar to the present is necessary to begin to understand what is undoubtedly a primitive yet profound human ability. Such research is necessary to explain some of the amazing feats of human navigation documented by Lynch (1960), Gladwin (1970), Lewis (1975), and others, and anecdotally chronicled for centuries.

NOTE

1. Our original intention was to analyze the pointing data with a *triangulation* analysis (Hardwick, McIntyre, & Pick, 1976). In this analysis, three directional estimates to the same landmark intersect to form an estimation triangle, the area of the triangle and the location of its center serving as measures of precision and accuracy, respectively. However, several of the pointing estimates did not intersect, leaving no way to define an estimation triangle. When this occurs, improved directional estimates are required to use triangulation.

REFERENCES

Bronzaft, A. L., Dobrow, S. B., & O'Hanlon, T. J. (1976). Spatial orientation in a subway system. *Environment and Behavior, 8*, 575-594.

Bryant, K. J. (1982). Personality correlates of sense of direction and geographical orientation. *Journal of Personality and Social Psychology, 43*, 1318-1324.

Chase, W. G., & Chi, M.T.H. (1981). Cognitive skill: Implications for spatial skills in large-scale environments. In J. H. Harvey (Ed.), *Cognition, social behavior, and the environment* (pp. 111-136). Hillsdale, NJ: Lawrence Erlbaum.

Evans, G. W., Fellows, J., Zorn, M., & Doty, K. (1980). Cognitive mapping and architecture. *Journal of Applied Psychology, 65*, 474-478.

Evans, G. W., Marrero, D. G., & Butler, P. (1981). Environmental learning and cognitive mapping. *Environment and Behavior, 13*, 83-104.

Foley, J. E., & Cohen, A. J. (1984a). Mental mapping of a megastructure. *Canadian Journal of Psychology, 38*, 440-453.

Foley, J. E., & Cohen, A. J. (1984b). Working mental representations of the environment. *Environment and Behavior, 16*, 713-729.

Garfin, D., & Pick, H. L. (1981, May). *Reaching out for spatial knowledge.* Paper presented at the meeting of the Midwest Psychological Association, Detroit, MI.

Gärling, T., Böök, A., Lindberg, E., & Arce, C. (1990). Is elevation encoded in cognitive maps? *Journal of Environmental Psychology, 10*, 341-351.

Gärling, T., Lindberg, E., & Mäntylä, T. (1983). Orientation in buildings: Effects of familiarity, visual access, and orientation aids. *Journal of Applied Psychology, 68*, 177-186.

Gladwin, T. (1970). *East is a big bird.* Cambridge, MA: Harvard University Press.

Hanley, G. L., & Levine, M. (1983). Spatial problem solving: The integration of independently learned cognitive maps. *Memory & Cognition, 11*, 415-422.

Hardwick, D. A., McIntyre, C. W., & Pick, H. L. (1976). The content and manipulation of cognitive maps in children and adults. *Monographs of the Society for Research in Child Development, 41*(3, Serial No. 166).

Hart, R. A., & Moore, G. T. (1973). The development of spatial cognition: A review. In R. M. Downs & D. Stea (Eds.), *Image and environment* (pp. 246-288). Chicago: Aldine.

Herman, J. F., Blomquist, S. L., & Klein, C. A. (1987). Children's and adults' cognitive maps of very large unfamiliar environments. *British Journal of Developmental Psychology, 5*, 61-72.

Herman, J. F., Kail, R. V., & Siegel, A. W. (1979). Cognitive maps of a college campus: A new look at freshman orientation. *Bulletin of the Psychonomic Society, 13*, 183-186.

Holding, C. S., & Holding, D. H. (1989). Acquisition of route network knowledge by males and females. *Journal of General Psychology, 116*, 29-41.

Kirasic, K. C., Allen, G. L., & Siegel, A. W. (1984). Expression of configurational knowledge of large-scale environments: Students' performance of cognitive tasks. *Environment and Behavior, 16*, 687-712.

Kozlowski, L. T., & Bryant, K. J. (1977). Sense of direction, spatial orientation, and cognitive maps. *Journal of Experimental Psychology: Human Perception and Performance, 3*, 590-598.

Landau, B., Spelke, E., & Gleitman, H. (1984). Spatial knowledge in a young blind child. *Cognition, 16*, 225-260.

Levine, M., Marchon, I., & Hanley, G. L. (1984). The placement and misplacement of you-are-here maps. *Environment and Behavior, 16*, 139-157.

Lewis, D. (1975). *We, the navigators: The ancient art of landfinding in the Pacific.* Honolulu: University of Hawaii Press.

Lindberg, E., & Gärling, T. (1981). Acquisition of locational information about reference points during blindfolded and sighted locomotion: Effects of a concurrent task and locomotion paths. *Scandinavian Journal of Psychology, 22*, 101-108.

Lynch, K. (1960). *The image of the city.* Cambridge, MA: MIT Press.

Moar, I., & Carleton, L. R. (1982). Memory for routes. *Quarterly Journal of Experimental Psychology, 34A*, 381-394.

Moeser, S. D. (1988). Cognitive mapping in a complex building. *Environment and Behavior, 20*, 21-49.

Moore, G. T. (1974). The development of environmental knowing: An overview of an interactional-constructivist theory and some data on within-individual development variations. In D. Canter & T. Lee (Eds.), *Psychology and the built environment* (pp. 184-194). London: Architectural Press.

Passini, R. (1984). *Wayfinding in architecture*. New York: Van Nostrand Reinhold.

Peponis, J., Zimring, C., & Choi, Y. K. (1990). Finding the building in wayfinding. *Environment and Behavior, 22*, 555-590.

Pick, H. L., & Rieser, J. J. (1982). Children's cognitive mapping. In M. Potegal (Ed.), *Spatial abilities: Development and physiological foundations* (pp. 107-128). New York: Academic Press.

Siegel, A. W., & White, S. H. (1975). The development of spatial representations of large-scale environments. In H. W. Reese (Ed.), *Advances in child development and behavior, Vol. 10* (pp. 9-55). New York: Academic Press.

Smyth, M. M., & Kennedy, J. E. (1982). Orientation and spatial representation within multiple frames of reference. *British Journal of Psychology, 73*, 527-535.

Sullivan, C. N., Montello, D. R., Pick, H. L., & Somerville, S. (1990). *Integration of spatial knowledge*. Unpublished manuscript.

Thorndyke, P. W., & Hayes-Roth, B. (1982). Differences in spatial knowledge acquired from maps and navigation. *Cognitive Psychology, 14*, 560-589.