Journal of Environmental Psychology (1997) **17**, 317–331 0272-4944/97/040317+15$25·00/0

Journal of ENVIRONMENTAL PSYCHOLOGY

TWO STRATEGIES FOR LEARNING A ROUTE IN A DRIVING SIMULATOR

VLADA AGINSKY[1], CATHERINE HARRIS[2], RONALD RENSINK[1] AND JACK BEUSMANS[1]

[1]*Cambridge Basic Research, Nissan R & D, Inc., 4 Cambridge Center, Cambridge, MA 02142, U.S.A.;*
[2]*Department of Psychology, 64 Cummington St, Boston University, MA 02115, U.S.A.*

Abstract

The study of human navigation has long been dominated by the so-called stage theory, i.e. the notion that there are three distinct types of spatial knowledge (landmark, route, and survey knowledge), that are acquired sequentially during spatial learning and development. Based on the results of a route learning experiment in a driving simulator, an alternative to the stage theory is proposed. The authors suggest that subjects follow either a visually dominated or a spatially dominated strategy to solve a route-learning problem. In the visually dominated strategy, subjects base their wayfinding decisions on visually recognizing decision points along a route; the decision points are not integrated into any kind of survey representation. In the spatially dominated strategy, on the other hand, subjects represent the environment as a survey map right from the start; that is, they do not pass through a landmark or route stage. These strategies may be subserved by different cortical areas recently characterized in neurophysiological studies of animals solving maze problems.

Introduction

When moving about in a large environment such as a city, humans learn a mental representation of that environment which enables them to follow familiar routes and to perhaps plan new ones. These mental representations have been the subject of numerous studies in human spatial cognition and development (Piaget & Inhelder, 1969; Hart & Moore, 1973; Siegel & White, 1975; Moore & Golledge, 1976; Evans, 1980; McDonald & Pellegrino, 1993). Investigators have sought to distinguish between different types of spatial knowledge (e.g. Lynch, 1960, who introduced the notions of landmarks, edges, routes, districts and nodes) and different ways of organizing that knowledge into so-called cognitive maps, the mental analogues of topographic maps.

It has been noted by a number of investigators that people organize their spatial knowledge either around routes or around spatial landmarks or districts, leading to so-called *route maps* and *survey maps*, respectively. The distinction between route and survey maps has perhaps been documented most thoroughly by Appleyard (1969*b*, 1970). As part of an effort to plan more rationally the rapid expansion of Ciudad Guayana in Venezuela, Appleyard interviewed hundreds of inhabitants of that city, asking them to draw sketch maps of the entire city and their local neighborhood (note that at that time no public maps of the area were available). These sketch maps were found to vary along two main dimensions, one being the type of primitive element from which the map was built, the other the level of accuracy and complexity. About 75% of all maps used sequential or route elements as their primitive, and 25% used spatial elements (buildings, landmarks, districts). The latter maps looked more like topographical survey maps, reflecting the spatial layout of the environment rather than the subject's direct navigational experience. Having thus classified the sketch maps, Appleyard then correlated map type with other variables such as mode of travel, familiarity, etc. Travel mode had the expected effect on map type: those mainly using cars to get around the city tended to draw more survey maps and those relying exclusively on buses only rarely produced coherent maps. The use of spatial elements increased somewhat with familiarity, but route elements predominated even in the local neighborhood maps.

These and related findings have been interpreted within a larger theoretical framework which posits that the stages of adult spatial learning mirror the developmental stages in spatial understanding identified in children. This theory was laid out quite explicitly by Siegel and White (1975), who summarized adult spatial learning as follows: first, landmarks are noticed and remembered ('recognition-in-context' learning system); second, route knowledge is acquired through paired associations of actions with landmarks ('stimulus–response pairing'); third, survey knowledge is obtained as routes become metricized and as more routes are learned ('configuration or structural learning'). Similarly, during development a child first learns to identify landmarks, then to associate actions with them and thus to form a route, and finally the child is able to assemble the routes into a survey representation using an objective, global reference frame. According to Siegel and White, then, learning and development parallel each other because the learning systems that become operative in succession during adult learning mature in that same sequence during development. Thus, the route maps in Appleyard's study are viewed as the primitive and necessary precursors of the survey maps.

But, as might be expected from such a bold and sweeping proposal, conceptual and methodological problems were identified and empirical results at variance with the hypothesis appeared (for a recent summary of the debate see Montello, in press). In the present paper, we will focus on issues relating to adult spatial learning.

First, is it meaningful to think of landmarks as entities independent and separate of routes? Of course, there are buildings and structures such as the Eiffel Tower or the Golden Gate Bridge, that are so striking and unique that they would be noticed and recalled by everybody independent of context. But what about the gas station where you make your right turn going to work? If it were not for the fact that it is on your route and you need to somehow remember to make a right turn there, the station would never be included in your route or survey map. This is exactly what Appleyard (1969*a*) found in his Ciudad Guayana study. In this study, 300 people were asked to recall as many places and buildings in the city as possible, then to draw a map of the city with these places and to add any others that came to mind, and finally to recall places along an imagined route through the city. Each element thus mentioned was described in terms of its visual features, size, location, significance, social use, etc. Of particular importance here is the so-called visibility rating of elements. Visibility was subdivided into three subcategories each of which could be rated low, medium or high: (1) viewpoint intensity (going from low to high intensity this means being visible from tertiary, secondary, or primary roads); (2) viewpoint significance (visible at points without any transition, at decision points on secondary roads, and at major decision points), and (3) immediacy (distant or poorly visible, distant but on axis of road, nearby and cutting across line of sight). Viewpoint significance and immediacy of buildings were correlated equally with recall frequency and about twice as much as viewpoint intensity. There were instances in which a particular building next to an intersection was recalled by many subjects, whereas an identical looking building away from an intersection was never mentioned. Thus, mere visibility of a building is not sufficient for its recall, but proximity to a decision point virtually guarantees it. This means that, in general, landmarks cannot be defined independent of routes; a building or other stable part of the environment acquires landmark status by virtue of being able to localize an action in space (see Biegler & Morris, 1993, 1996, about the importance of landmark stability in spatial learning in rats).

Second, the progression from landmark to route to survey knowledge is presented as occurring more or less automatically as experience increases. But what does experience mean? How does one decide that person A has more experience than person B? A passenger in a car may be exposed to similar visual stimuli as the driver, but will have a very different experience. Duration of exposure or residence in a city as a measure of experience is at best a first-order approximation, which on occasion can be quite inappropriate (Evans, 1980; McDonald & Pellegrino, 1993). As Passini (1984; Arthur & Passini, 1992) has emphasized, wayfinding as a problem-solving activity is pragmatic: one learns what is necessary and sufficient to achieve a goal. Thus, Moeser (1988) found that even after working for two years in a hospital building, student nurses still had not formed anything resembling survey maps of this admittedly complicated building; they had apparently developed other strategies and the corresponding mental representations to meet their wayfinding needs. Similarly, the richness of their environment determines whether rats will be place-learners (cue-rich environment) or response-learners (cue-poor environment) (MacDonald & Pellegrino, 1993). In this light, route maps and survey maps may simply be different but equally valid solutions to a wayfinding problem. These observations also point to the importance of knowing the exact instructions given to subjects in a spatial learning task, as the instructions will influence what a person learns and pays attention to during learning.

Third, are the mental processes involved in landmark recognition and route or survey map construction as posited by Siegel and White (1975) really all that different? Consider, for example, the case of a teenage patient with right posterior hemispheric lesions (Clarke *et al*., 1993). This patient was unable to recognize well-known landmarks from their general appearance, as normal subjects do, but instead relied on a propositional description of the features identifying the landmarks. She could learn the spatial relationships of objects inside a small space such as a room but was unable to do so for buildings or towns. Routes were painstakingly memorized as sequences of decisions at places identified by some unique feature (this shows that it is hard to use distinguishing features rather than general appearance to recognize a scene or other complex object because you would have to know *where* to look; if you do not remember where to look, you would have to systematically search for possible distinguishing features). Besides space, time was also linear for her; to determine whether she would have time for a meeting say next Friday, she would have to go through all the days between now and then; she was unable to refer directly to Friday. It is as if she was unable to organize events separated in space or time in a two-dimensional framework (be it an image, route, map, or schedule). Thus, the right posterior parietal lesions in this patient affect all three “stages” in spatial learning in a similar way, suggesting that these stages are subserved by the same fundamental learning process.

Recent experiments on spatial learning in rats and on spatial orientation in animals and human infants further illustrate the difficulty of considering landmark knowledge as separate from and prior to route and (local) survey knowledge. These experiments suggest almost the opposite learning sequence, namely that some survey knowledge is required to learn about landmarks. Biegler and Morris (1993, 1996) found that landmark stability is necessary for rats to learn the location of a food source. Animals did not learn the location of food by simply associating it with a local landmark; in fact, increasing the salience of the landmark decreased spatial learning. Similarly, Gallistel and Cramer (1996) found that the location of food in a global frame of reference takes precedence over the association of the food source with unique local visual and olfactory cues. The same was found for human infants (Hermer & Spelke, 1994).

Taken together, these considerations suggest an alternative interpretation of the differences between route and survey maps. Rather than viewing route maps as precursors of survey maps, we consider them to result from a different strategy for solving a navigational problem. For example, route maps may result from relying more on egocentric representations, survey maps from using allocentric representations. Neurophysiological studies have associated the former with prefrontal cortical areas, the latter with parietal areas (Traverse & Latto, 1986; Kesner *et al*., 1989).

The goal of our experiment then is to gain further insight into the strategies used in adult spatial learning. The subjects in our experiment had to learn a route through a virtual world in a driving simulator. Immediately upon learning the route, the subjects’ visual and spatial knowledge was tested. The rationale behind this design is that if route knowledge precedes survey knowledge, then we would expect to find only route knowledge after this limited exposure to the virtual world with the express goal of learning a route. If route and survey knowledge are the result of different approaches to this wayfinding problem, then we would expect to see both route and survey knowledge and to perhaps find other differences in visual or spatial knowledge.

A driving simulator offers the opportunity of studying fairly realistic active navigation in a controlled environment. It combines the advantages of studying spatial learning in a real-world setting (active, purposeful exploration) with those of spatial learning from a series of pictures or video (controlled visual input and identical subject experience). The disadvantages of using a driving simulator are that the virtual world is obviously not as rich as the real world and that so-called idiothetic inputs are absent. Idiothetic inputs are internally generated sensory signals associated with actual body displacements; they include motor efference copies and signals from the vestibular and proprioceptive systems. In a stationary driving simulator, idiothetic information conflicts with visual and auditory information, which can lead to motion sickness. We do not consider the absence of idiothetic input to be a problem for our purposes as vision tends to override idiothetic information when the two are in conflict (e.g. vection in humans, moving train illusion); even in rodents, visual landmark information overrides conflicting idiothetic information (Goodridge and Taube, 1995; Taube and Burton, 1995).

Materials and Methods

Driving simulator

The fixed-base driving simulator consisted of the front two-thirds of a Nissan 240SX convertible. The 'control' computer (33 MHz i486 Dell 433M PC) managed the data I/O and local closed-loop control of the active kinesthetic feedback, that is, steering wheel torque. Steering wheel torque was generated by an AC motor attached to the steering column, with a peak torque of 5·6 Nm and a sustained value of 2·8 Nm. These values are within the range of normal driving on a highway. The control computer also generated audio feedback to the driver in the form of low-frequency engine noise, whose frequency was proportional to driving speed.

The 'graphics' computer (Indigo^2 Extreme workstation, Silicon Graphics, Inc.) was connected to the control computer by a serial connection and updated both the car and world models. The graphics computer also rendered the virtual world, which was projected onto a wall 3·5 m in front of the driver using a Barco 800G. The projected image was 60 degrees wide and 40 degrees high. The frame rate was on average 12 frames/s during the experiment.

Virtual world

The virtual world consisted of a road system with about 50 intersections of varying complexity, laid out on a 350 by 630 meters green, textured ground plane. See Figure 1 for a map and Figure 2a for a sample scene from the world.

The only objects in the world besides the roads and intersections were 24 rectangular buildings concentrated along the route subjects had to learn. Half of the buildings were 'wide' (28 m wide, 15 m deep, and 12 m high), and half were 'tall' (10 m wide, 10 m deep, and 16 m high). Of the 12 wide (tall) buildings, half were blue and half were red. The different sides of each building varied a little in brightness in order to make the buildings appear more three-dimensional. Thus, there were only four types of buildings: (i) wide and red, (ii) wide and blue, (iii) tall and red, and (iv) tall and blue.

A blueish fog was used to reduce flicker caused by pixels associated with distant objects, mainly roads, going on and off between successive frames. The fog added to the impression of depth in the scene as distant buildings and roads appeared more blue (aerial perspective). The fog caused buildings to become gradually visible at a distance of about 150 m (the distance between building 7 and 9 in Figure 1).

Procedures

The experiment was divided into a learning phase and a test phase. During the learning phase, subjects had to learn a 1770-m long route through the virtual world, which took 2 to 4 minutes (see Figure 1 for the route). Subjects controlled their own speed and direction. Subjects were only told to learn a route; they were not informed about the tests that were to follow the learning phase. Thus, subjects were not told explicitly to pay attention to the buildings or to memorize them, and they did not know that they had to draw a map of the route at the end of the experiment.

Subjects were led along the experimental route by verbal directions of the experimenter. The instructions consisted only of the phrases 'take the next right' or 'take the next left', without any reference to buildings or particular intersections. As learning progressed, the experimenter offered instructions only for the turns which the subjects had not yet memorized. The subjects indicated which turns they knew by using the car's direction signals before they turned. They repeated the drive until they could follow the route correctly once without any help from the experimenter.

Immediately following the learning phase, the subjects' spatial knowledge was assessed by three tests. Two of the tests were outside the context of the environment—the scene and route recognition test (first test) and the drawing of the sketch map (third test)—and one was within the virtual environment, while following the route—the detection of building changes (second test). Before the building changes test, subjects drove the route one more time to refresh their memory of the buildings and the layout. All subjects could still follow the route on their own.

Sketch maps

Subjects were given a blank sheet of paper [11 by 17 inches (approx. 28 by 43·18 cm)] and asked to 'draw a map of the route, as accurately as you can, and include as much as you can recall.'

The sketch map is used to externalize a subject's mental representation or knowledge of the spatial layout of some part of the environment. As such, one must be concerned to what extent sketch maps merely reflect a subject's drawing ability rather than spatial knowledge. A study comparing the accuracy of sketch maps of home floor plans with artistic ability in adults found only a very weak correlation (Rothwell, 1976, as quoted by Evans, 1980).

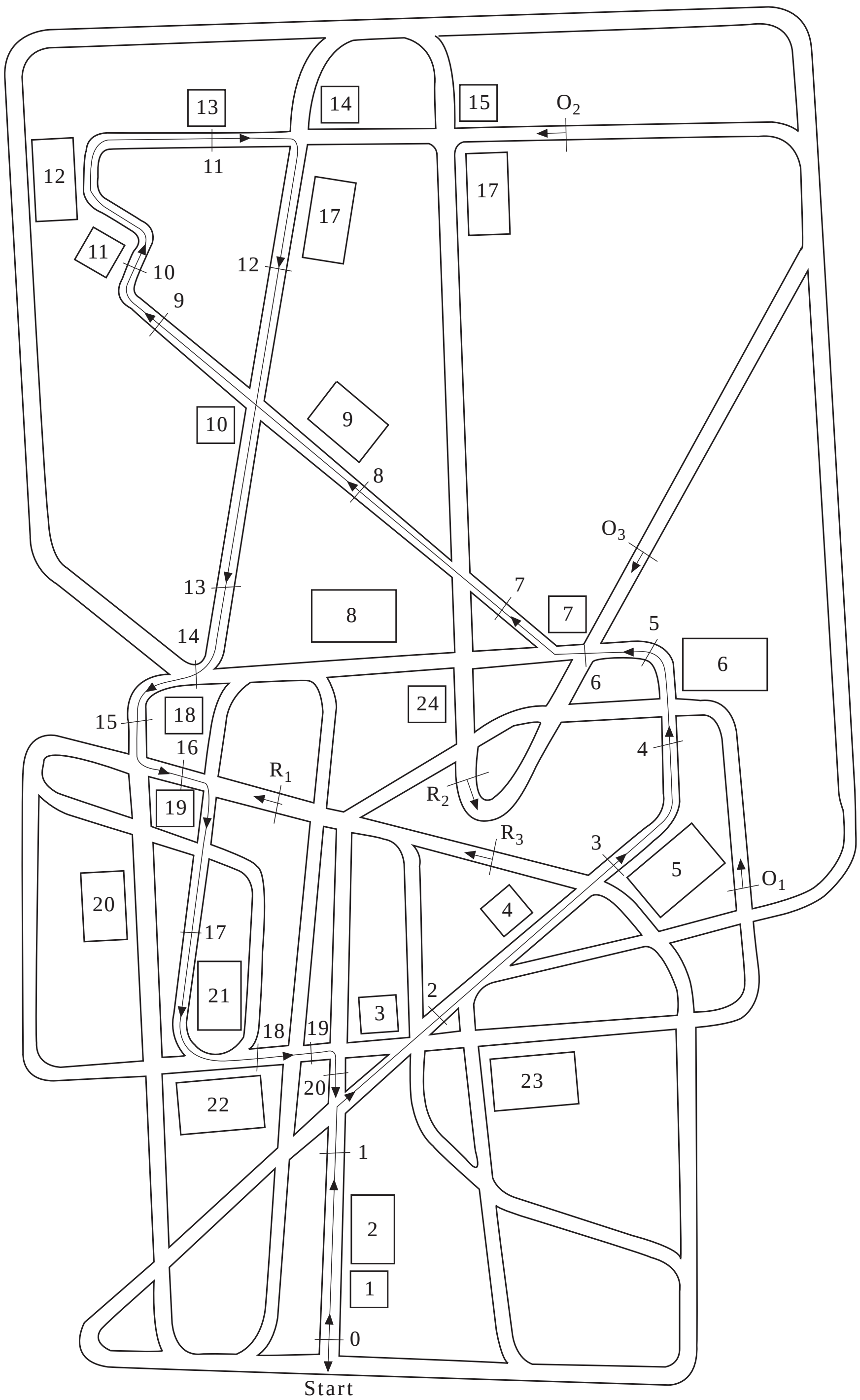

FIGURE 1. Map of the virtual world showing the location of buildings and the route subjects had to learn. Numbers along the route indicate the vantage points of the snapshots used in the experiment. The snapshots O_1, O_2 and O_3 were the non-route snapshots used in the ordered presentation; R_1, R_2 and R_3 were used in the random presentation.

Moore (1976) found that sketch maps of high school students are quite reliable, that independent judges could reliably classify these sketch maps to one of three levels (see below), and that this classification was stable over time (subjects drew a second map after one month). Furthermore, sketch map level correlated significantly with performance on various verbal wayfinding tasks, suggesting that the sketch maps reflected spatial knowledge. Given these results, we believe that sketch maps were a reasonable way of evaluating a subject's spatial knowledge in our study.

Visual scene and route recognition

Subjects viewed two sets of 24 static scenes or snapshots; 21 of these snapshots were identical and were taken from along the route subjects had just learned, and three snapshots were of areas of the world subjects had never visited (nonroute scenes); the nonroute snapshots differed in the two sets to avoid the possibility that they would appear to be familiar in the second set after having seen them in the first set. See Figure 1 for the vantage points of all snapshots.

The 21 route snapshots can be divided into three equally sized classes depending on the decision subjects had to make:

(1) *No choice road sections* (scenes 0, 3, 9, 10, 12, 13, 17). The visible road offers no choice.
(2) *Passive intersections* (scenes 2, 4, 5, 7, 8, 18, 20). There is an intersection offering a choice but the route continues straight ahead so that subjects can just naturally follow the road. All scenes except No. 2 offer three choices (left, right, straight).
(3) *Active intersections* (scenes 1, 6, 11, 14, 15, 16, 19). There is an intersection and the route deviates to the left or right, requiring subjects to decide to turn left or right. All scenes except No. 6 and No. 14 offer three choices.

One set of snapshots presented the scenes in the order in which they were encountered along the route (*ordered* presentation), but with three nonroute scenes interspersed. The other set presented the same scenes in random order (*randomized* presentation). Half of the subjects saw the ordered scenes first; the other half saw the randomized scenes first. The average number of buildings per scene was 3·4; the minimum was 1 and the maximum was 6.

Upon presentation of a scene, subjects had to decide as quickly as possible whether they should turn right, left, or follow the road in the scene. They used the turn signal lever to register their responses (pulling the lever towards themselves for 'follow the road'). Subjects were told to guess if they did not recognize a scene. Reaction times of all responses were recorded (resolution 14 ms).

After subjects had given their direction response, a small vertical rating scale appeared in the top half of the screen. Using the turn signal lever, subjects had to bring the scale indicator to the point representing the scene's familiarity. The top of the scale represented complete recognition, which was recorded as '1' and the bottom represented no recognition, which was recorded as '0'. Once the indicator was at the desired place on the scale, the subjects pressed a button in the middle of the steering wheel. This response blanked the screen; after 5 seconds the next scene appeared. Five practice scenes were given before the first series was shown.

Detecting building changes

Subjects drove the route they had previously learned, but now 11 of the 24 buildings had been changed. The subjects were told that about half the landmarks would be different in some manner but were not told in advance what the changes could be. While driving along the route, subjects had to verbally indicate any differences they noticed. The experimenter recorded what the subjects said and how they were driving.

The 11 target buildings changed in either color (red to blue, and vice versa), shape (tall and thin to short and wide, and vice versa), or color and shape. Buildings could also change their location (cross to the other side of the street), and with it their color or shape. Subjects, however, did not think of these 'location changes' as the change in location of an identifiable building; instead they interpreted it as the disappearance of the old building and the appearance of a new one (especially if the color and shape were different from the old building). We will continue to use the term 'location change' as a shorthand to refer to these building manipulations.

Table 2 lists all the building changes, and Figure 2 shows an example of two building changes.

Subjects

Sixteen MIT undergraduates from various engineering disciplines and people working in the MIT area participated as paid volunteers (10 men and six women; ages 19 through 25). All subjects were naive as to the purpose of the experiment.

Results and discussion

Subjects learned the route using an average of 7·7± 1·4 (S.D.) repetitions. The minimum number required was six (five subjects) and the maximum

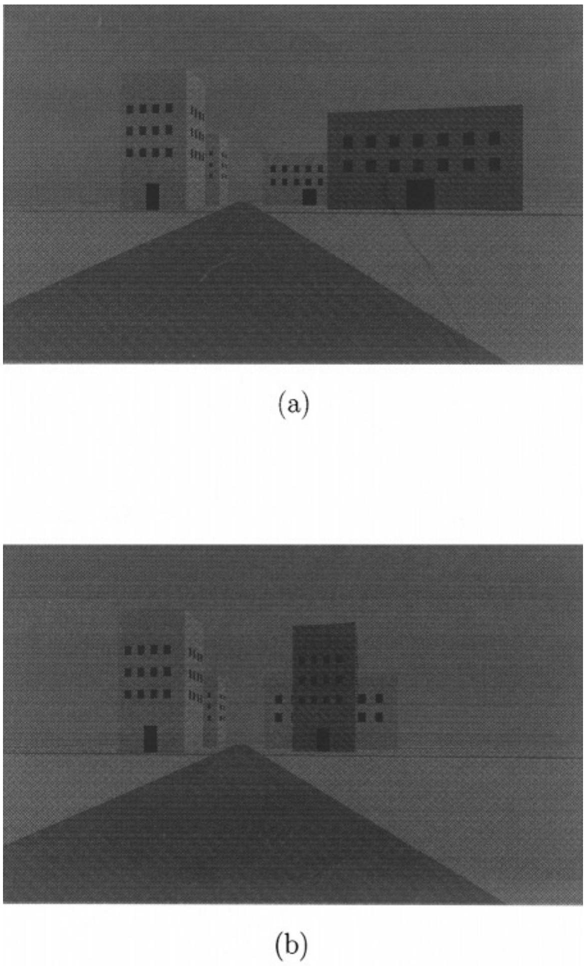

FIGURE 2. Scene 11 before (a) and after (b) two of its buildings had changed. The building in the foreground changed from tall to wide, and the building behind it came closer.

was 10 (two subjects). The average time for completing the route once ranged from 2 to 3 minutes. Subjects who needed fewer repeats to learn the route, tended to complete the route somewhat faster (this correlation was not significant, $F(1,14)=1{\cdot}7$, $p=0{\cdot}2$). See Table 1 under 'route learning' for individual subject data. Only one subject realized that the start and finish of the route were at the same location.

Sketch maps

Sketch maps rarely reflected the correct metric relationships among identifiable locations in the virtual world, including distinct locations that followed each other. Turns and bends were typically drawn as right-angle turns even if they were not, and areas with many turns or bends were enlarged at the expense of straight road segments (see also Byrne, 1979; Tversky, 1981). The relative lengths of the straight road segments were often reproduced inaccurately. For example, the road segment between buildings 7 and 11 is 1·1 times as long as the segment between buildings 17 and 18. In the 10 sketch maps (out of the 16 total) in which these segments could be measured, this ratio varied from 0·5 to 2.

Sketch maps generally preserved the linear relationships between road segments and in most sketch maps it was easy to recognize the following distinct *places* along the route:

(1) beginning of the route with an immediate turn to the right, followed by
(2) two left bends, each at a building, then a
(3) right turn behind the red building on the right,
(4) a few turns in front of two buildings,
(5) a sharp right turn in front of a long blue building,
(6) a characteristic turn to the right in front of and past a building followed by a quick left and right turn.
(7) a characteristic bend to the left behind a building, and finally
(8) a right turn on the second street to reach the end of the route.

Places 1, 2, 3, 4, and 8 were almost always included, whereas places 5, 6 and 7 were omitted by an average of five subjects. Very little extraneous information was included in the sketch maps. For example, the intersections between buildings 3 and 6 were included by only two subjects, those between buildings 7 and 11 by three subjects. More details were included at places. At place 6, for instance, 10 subjects included an extra road to show more clearly how the route passed behind building 18.

Evaluating and ranking a set of sketch maps is notoriously difficult because of the high variability between subjects. We tried to make our ranking as objective as possible by defining a number of explicit rules for evaluating the sketch maps and by comparing two separate, independent evaluations (by authors VA and JB). The quality of sketch maps was quantified according to: (i) their topological accuracy; (ii) the number of buildings included; (iii) the number of correct and incorrect turns; and (iv) the accuracy of relative distances in the sketch map.

The topology of sketch maps was quantified by the number of crossings included (maximum is two: start and finish were at the same location and the crossing at building 10) and the number of breaks or discontinuities in the sketch map.

The correctness of the map was quantified as the number of correct turns minus the number of incorrect extra turns and the number of omitted turns. The turn angles and the relative directions and lengths of the road segments were ignored. Since the route has a total of 15 turns, 15 is a perfect score.

The accuracy of route segment lengths in a sketch map was quantified by measuring the lengths of the eight major route segments and counting the number of adjacent segments that had the correct relative relationship (i.e. larger than or smaller than). As there were eight segments, the maximum score is seven.

Table 1 lists the various sketch map descriptors as well as the time it took for each subject to learn the route. Based on the connectivity of places in the sketch map, the extent to which it reflected the use of a global frame of reference, the number of correct turns, and the degree to which distances in the sketch map reflected actual distances, three types of sketch maps could be distinguished (see Figure 3 for canonical examples):

(1) *0-D Place* type. (19% of subjects). Isolated places, each with some local spatial structure. Places often include information for their recognition. The sketch map of CD in Figure 3 actually repeats place 6; first to show its characteristic road pattern as it appears during approach, and then to show how the route meanders at that location. Route segment lengths are not represented accurately if at all (mean score 0·7±0·7).

(2) *1-D Place* type. (50% of subjects). Places that had been encountered sequentially are explicitly connected but there is little global structure. Route segment lengths differ considerably from actual distances (mean score 1·6±0·4). Places tend to be enlarged; straight sections often merely connect successive places. Sometimes successive places are not in the right order; AM's map in Figure 3 shows an example of transposition, the switching of two places.

(3) *2-D Place* type. (31% of subjects). Places that had been encountered sequentially are connected; some of the places that had not been encountered in sequence are connected spatially. Route segment lengths are represented accurately (mean score 4·8±0·9, which differs significantly from the 0-D and 1-D group scores). Places tend not to be enlarged compared to straight sections.

TABLE 1.
Evaluation and classification of sketch maps into 0-D, 1-D and 2-D types

Ss*	Route learning†		Buildings included‡	Map descriptors			Map type**
				topology§	turns¶	dist‖	
cd	8	162	6	0–5	4	0	0
es	9	127	0	0–2	5	0	0
er	8	202	2	0–1	12	2	0
ma	8	167	5	0–0	2	0	1
ea	7	164	2	0–1	3	2	1
pm	10	140	6	0–0	4	3	1
jd	6	160	0	0–0	5	1	1
am	10	168	6	0–2	6	2	1
mp	8	137	0	0–0	6	1	1
dn	7	145	0	0–0	9	3	1
dh	6	183	19	0–0	12	1	1
lt	9	139	2	1–1	7	2	2
bg	9	175	0	0–0	13	4	2
jz	6	141	9	0–0	13	5	2
le	6	178	8	1–0	13	6	2
ml	6	193	11	1–0	15	7	2

*Bold face indicates female subject.
†Number of drives and mean time to complete the route in seconds.
‡Number of buildings included (maximum is 24).
§Number of crossings and the number of breaks in the sketch map.
¶Number of correct turns minus number of incorrect ones (maximum is 15).
‖Number of adjacent route segments with correct relative sizes (maximum is 7).
**Sketch map type: 0=0-D, 1=1-D, 2=2-D place type.

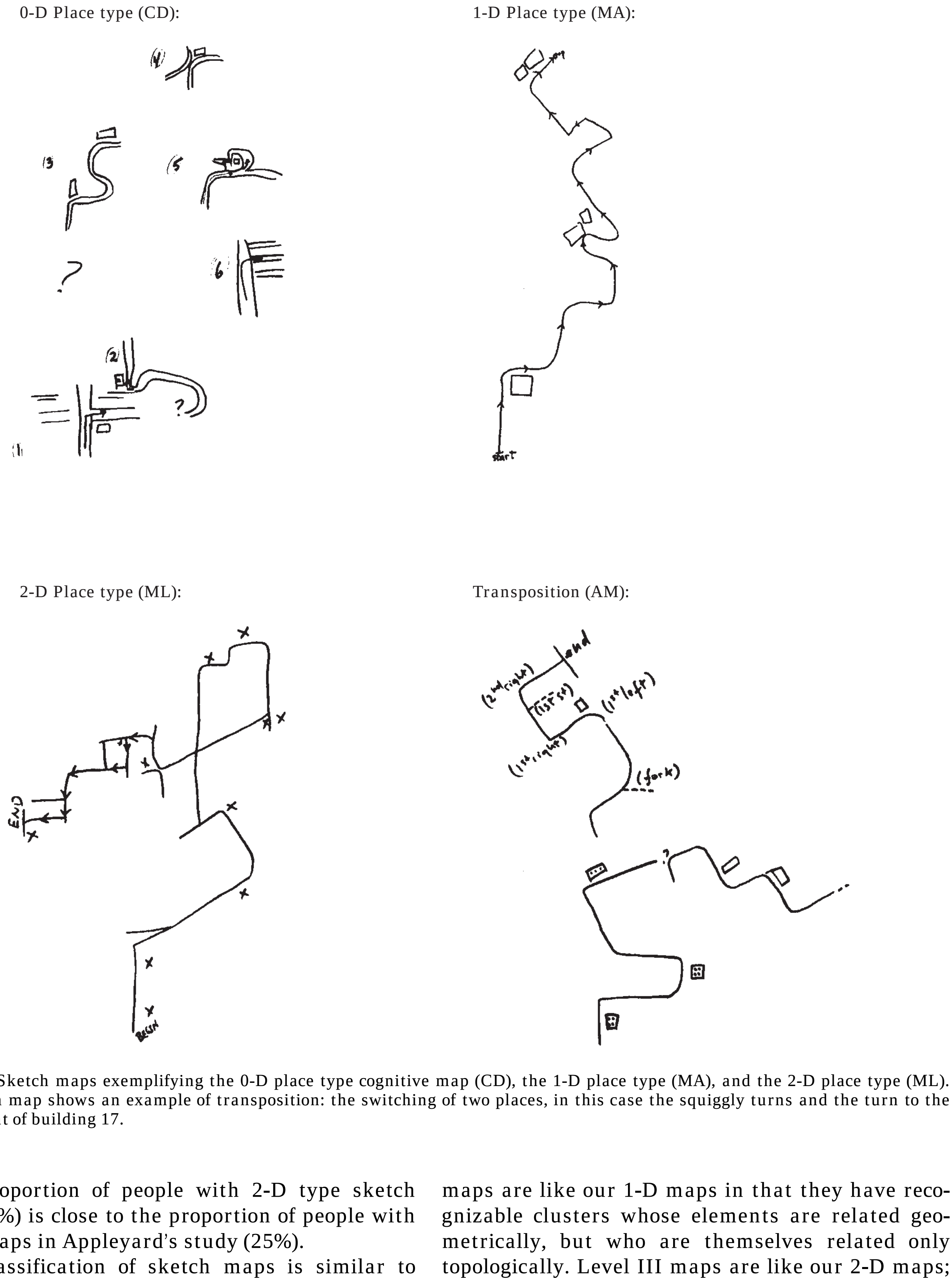

FIGURE 3. Sketch maps exemplifying the 0-D place type cognitive map (CD), the 1-D place type (MA), and the 2-D place type (ML). AM's sketch map shows an example of transposition: the switching of two places, in this case the squiggly turns and the turn to the right in front of building 17.

The proportion of people with 2-D type sketch maps (31%) is close to the proportion of people with spatial maps in Appleyard's study (25%).

Our classification of sketch maps is similar to Moore's (1976), who also distinguished among three levels. His Level I sketch maps correspond to our 0-D maps; these maps are undifferentiated, egocentric and organized only topologically. Level II sketch maps are like our 1-D maps in that they have recognizable clusters whose elements are related geometrically, but who are themselves related only topologically. Level III maps are like our 2-D maps; both resemble topographic maps in that they use a global frame of reference for all elements and have clusters that are less evident than in level II maps.

Finally, we found no correlation between gender and sketch map type or any of the sketch map descriptors, which agrees with other studies on the relationship between gender and spatial ability in the context of navigation (Moore, 1976; Self *et al.*, 1992; Golledge *et al.*, 1995).

Visual scene and route recognition

The results of the snapshot test were analyzed in three different ways. First, results were averaged over all subjects and over all snapshots. Second, results were averaged over all subjects and analyzed for each snapshot separately. Third, data of subjects were grouped according to their sketch map type (0-D, 1-D, 2-D) and the effect of presentation order was analyzed within each group.

First, averaged over all subjects, there were only small effects of presentation order and intersection type on scene and route recognition. Direction responses were correct 75% of the time for passive intersections and 66% of the time for active intersections during ordered presentations. During random presentations, recognition was slightly worse: 74% and 57% correct, respectively. Note that this performance was still significantly above change which would have been 36% for passive intersections and 38% for active intersections. The differences between active and passive intersections were not significant. Familiarity ratings were significantly higher for the no-choice scenes, which may reflect a higher confidence of the subjects in their response rather than a higher familiarity of these scenes. In general, if a correct direction choice was given for a scene, then it was also rated as more familiar. Reaction times (RTs) for the direction responses ranged from 2 to 6 s across subjects. Overall, the mean and S.E.M. for the median RTs for ordered (random) presentations were 3·0 s±0·3 (3.3± 0·3). RTs tended to be faster during ordered presentations, but the differences were not significant.

Second, analyzing the response measures for the scenes separately showed that responses varied considerably across scenes, in particular among the active intersections (Figure 4). For example, active scene 14 received the highest ratings, whereas active scene 1 received the lowest. Scene 14 occurred somewhere in the middle of the route and showed a peculiar bend in the road in front of a building, making it easy to remember that the route went past that building. In contrast, scene 1 was at the beginning of the route and did not have anything that made it stand out; and being at the start of the route, subjects might not have paid much attention to the surroundings. Familiarity ratings

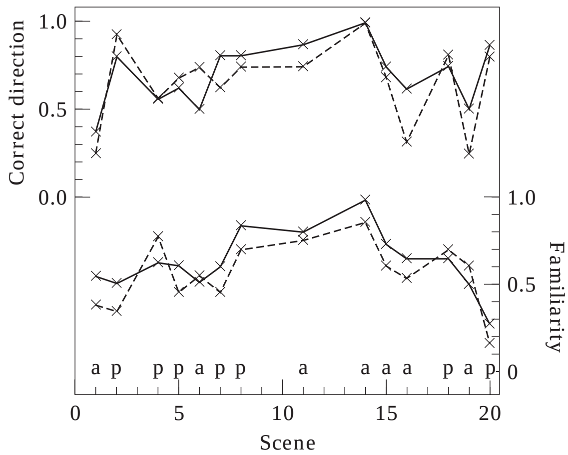

FIGURE 4. Mean direction responses and familiarity ratings for the 14 scenes with a choice (a=active and p=passive intersection). (—), ordered; (---), randomized.

in the random and ordered presentations were correlated significantly. Direction responses in the random and ordered presentation orders were correlated only for active scenes.

Third, grouping the subjects by their sketch map type uncovered an interesting and highly significant pattern. As Figure 5 shows, performance of the subjects with 0-D and 1-D sketch maps did not differ at all between the ordered and random presentations. In contrast, performance of the 2-D subjects was markedly worse during the random presentation. (This difference in performance was not an accidental consequence of the fact that all the 2-D subjects happened to have received the ordered presentation before the random presentation; in fact, three of the five 2-D type subjects received the random presentation first.) Direction responses dropped from 81% correct to 56% correct (t-value in paired t-test was –0·9, p=0·0008); reaction times increased from 3·3 to 4·3 s (t=3·0, p=0·04); and familiarity ratings dropped from 0·73 to 0·59 (t=5·2; p= 0·007). All five subjects with the 2-D sketch maps showed this drop in performance across the three response measures. Two of the other three subjects who had a similar but less pronounced drop in performance had many correct turns in their sketch maps (subjects ER and DH with 12 correct turns). Their maps had not been categorized as 2-D because their sketch map distances were inconsistent with the actual distances. Also note that the performance of the 2-D group during the random presentation was significantly worse than that of the 0-D and 1-D groups (p=0·005 in both cases).

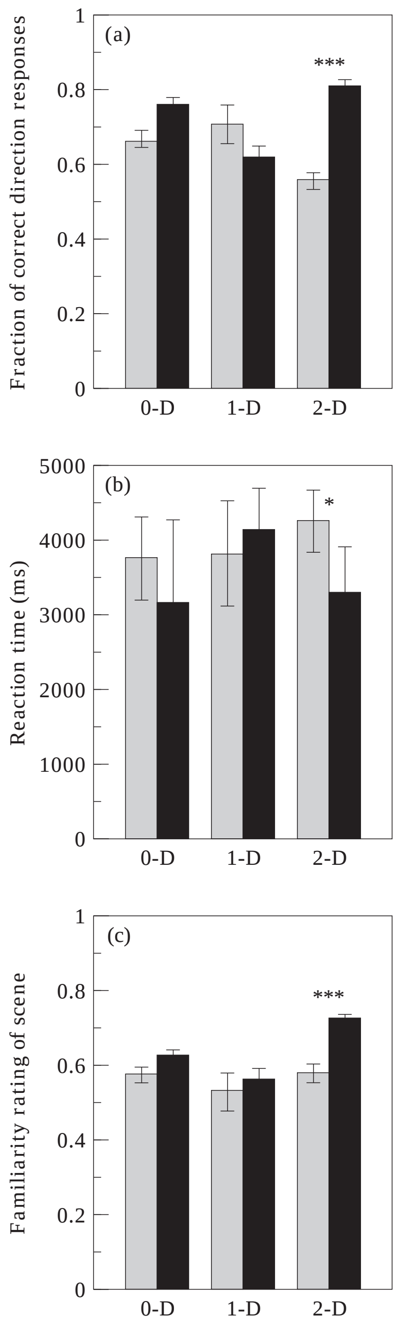

FIGURE 5. Scene and route recognition performance by sketch map type (0-D, 1-D, 2-D) and presentation order (random, ordered). (a) Fraction correct direction responses. (b) Mean reaction time (ms) of direction responses. (c) Familiarity rating of scene. Error bars are standard errors of the mean. (▨), random; (■), ordered.

Detecting building changes

Building changes were noted much more often at active intersections than at passive intersections where subjects could just follow the road. As shown in Table 2, changes were verbally noted 77% of the time at active intersections compared to only 26% of the time for passive intersections or straight road sections (difference was significant at p=0·001). The false alarm rate was very low: subjects wrongly reported a change in color five times, and a change in location only twice.

Changes in location were noted more often than changes in either color or shape (39%, 24% and 24%, respectively), and changes in shape were noted only when they occurred in isolation and not when they occurred in combination with either a change in location or in color. The failure to note a change of shape in conjunction with a location change can be explained by the fact that most subjects treated a 'location change' as a disappearance of one building and the appearance of a new one.

Figure 6 shows the results grouped by sketch map type. The three groups did not differ in the detection of changes at active intersections, but at passive intersections the 2-D group detected twice as many changes as either the 0-D or 1-D group, although these differences were statistically not significant. The slight superiority of 2-D types is consistent with the snapshot results which showed that 2-D types can recognize scenes better than 0-D or 1-D types if and only if the scenes are shown in order, that is, occur in a context which allows the 2-D type subjects to maintain a survey map throughout.

The navigation performance of six subjects was affected by the building changes. Some subjects obviously missed turns because they were anticipating to see a particular building. Although the number of mistakes were too few for statistical analysis, it is interesting that none of the 2-D subjects made an error and that, on average, the 1-D subjects made half an error and the 0-D subjects made one error.

The number of building changes noted was not correlated with the number of repetitions during learning or the duration of the learning phase, but it was significantly correlated with the number of correct turns in the sketch map (F(1,14)=5·45, p= 0·035).

Two other studies have noted previously that the closer landmarks are to route decision points the better they will be remembered. Appleyard (1969*a*) found a significant correlation between recall frequencies and 'viewpoint significance' of buildings, i.e. the extent to which a building is associated with a decision point along routes. Cohen and Schuepfer (1980) found that second graders, sixth graders and college students recall landmarks close to turns better than landmarks elsewhere along a route (note

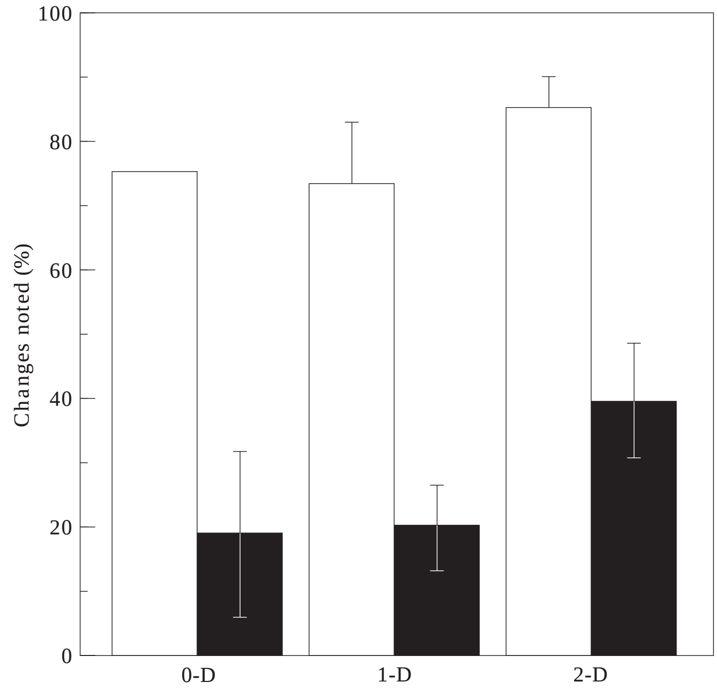

FIGURE 6. Mean percentage of building changes noted per subject by sketch map type and whether the change occurred in the vicinity of an active (□) or passive (■) intersection. Error bars are standard errors of the mean.

that subjects were explicitly instructed to memorize landmarks).

Conclusions

Two major conclusions can be drawn from the present study. First, subjects follow one or two strategies in learning a route, resulting in different mental representations. Second, subjects are very selective in picking up information from the environment; only information in the vicinity of choice point is retained.

All subjects in our study had reached approximately the same level of competence, that is, they had all learned to follow a route through a virtual world. Thus, the differences in performance encountered on the various tests are unlikely to reflect stages in spatial learning; rather, they would appear to reflect differences in handling the way-finding problem itself. We found that subjects could be divided into three groups based on the structure and quality of their sketch maps (0-D, 1-D, and 2-D place types). Of these groups, only the 2-D group was affected significantly by presentation order in the scene recognition test; and that group's performance during the random presentation was significantly below that of either the 0-D or 1-D group. The 2-D group was the only group for which building changes did not cause navigation errors.

The consistent differences in performance

TABLE 2.
Types of building changes and their detection

Building change	Active intersections				Passive intersections								
	19	7	11*	17	1	1†	16	4	21	10	10†	5	22
Color		x						x	x	x	x	x	
Shape	x		x	x				x	x				x
Location	x	x			x	x	x					x	x
% Noted	94	69	75	69	38	50	6	13	44	19	6	50	6
Mean±S.E.M.		77±6							26±7				

*Even though this building was not at an intersection, it was considered to be at an active part of the route because the route was locally hard to navigate, requiring considerable attention.
‡Encountered again at the end of the route.

between the 2-D group on the one hand and the 0-D and 1-D on the other, point towards two strategies in wayfinding, a visually dominated and a spatially dominated one. The fact that the 2-D group performed worse than the 0-D and 1-D groups in some tests shows that the former cannot be considered as simply superior across the board, as might be concluded from their superior sketch maps.

The visually dominated wayfinding strategy relies on the visual recognition of 'active' intersections along the route (e.g. 'turn right at the red building'). If a particular intersection is not recognized (due to a change in one of the buildings, say) the turn will be missed.

The spatially dominated wayfinding strategy relies on a mental map incorporating aspects of the environment's spatial structure. Although scenes and landmarks are still recognized visually, their recognition is not used directly for navigational purposes but is used to update one's mental map position. The ability of the 2-D-type subjects to orient themselves on a mental map would explain why they performed better with the ordered presentation of snapshots. The ordered snapshots resulted in a sense of position strong enough to prime the recognition of upcoming visual scenes. Our data are consistent with this interpretation but do not exclude the possibility that priming is between visual images of scenes, rather than between visual locations on a mental map. Either way, our results extend the phenomenon of priming (e.g. McNamara, 1986, 1992) to the navigational context. We believe that the linear ordering of places in the 1-D group does not reflect a genuine (spatial) representation that might lead to priming. Instead, we consider their ordering to be of a logical and *post hoc* nature and believe that the 0-D and 1-D groups really only differ in style, as the 0-D subjects clearly realized that certain places followed each other along the route and could have connected them in their sketch maps. Indeed, one of the 0-D subjects numbered the various places (CD in Figure 3). This interpretation is corroborated further by the fact that the 1-D group represented adjacent route segments lengths very inaccurately, resulting in a score that did not differ significantly from that of the 0-D group (see Section 3·1).

The above description of the visual and spatial wayfinding strategies is of course rather crude and simplistic. It is probably too simplistic to rigidly assign a subject to either one or the other strategy; subjects may use different strategies at different parts of a route, and may switch strategies depending on the exact details of the task. For example, some of the 0-D and 1-D type subjects clearly had some understanding of the spatial configuration of roads in the neighborhood of certain places.

The two wayfinding strategies may be subserved by different cortical areas recently characterized in neurophysiological studies of rats and monkeys solving maze problems (e.g. Traverse & Latto, 1986; Kesner *et al*., 1989; Paillard, 1990). The visually dominated strategy may depend more on prefrontal cortical areas, which encode more egocentric representations, whereas the spatially dominated strategy may rely on parietal cortex, which uses more allocentric representations. This is consistent with the idea that subjects using the spatially dominated strategy are better able to form an 'image' of their environment in the sense of Lynch (1960). And the lack of this ability may be the cause of the topographic disorientation described in Clarke *et al*. (1993).

Other studies have also found that, contrary to Siegel and White's (1976) stage theory, survey-type information can be acquired simultaneously with route information (Lindberg & Garling, 1982; Moar & Carleton, 1982; Holding & Holding, 1989; Hirtle & Heidorn, 1993). For example, Devlin (1976) compared sketch maps drawn first after only two weeks in a new city (Idaho Falls, Idaho) and a second time after three months. The first maps were already quite accurate; the second ones were elaborations of the first ones rather than qualitatively different maps. Devlin (1976) suggested that if structural changes occur during learning, they must occur very early on during the first hours or days.

Hirtle and Hudson (1991) found evidence of 'route' and 'survey' type knowledge after only two exposures to a route similar in complexity to ours (1600 m long with seven turns and 16 identifiable landmarks such as a post office, presented using slides taken every 20 m). After being exposed to the route twice, subjects verbally recalled the landmarks they had encountered along the route (note that each subject recalled the landmarks 16 times) and estimated straight-line distances. The lists of landmarks recalled were analyzed using an ordered tree clustering algorithm to determine the structure of a subject's cognitive map. The subjects who tended to recall landmarks in the same order (seven out of 16 subjects) were significantly worse at judging straight-line distances than subjects who recalled landmarks in varying orders. Presumably, the latter had formed a survey type map of the environment, which allowed them equal access to all the landmarks.

The second main conclusion from the present study is that subjects only retain information from around choice points along the route and that mere changes in heading are usually not sufficient to trigger information pick-up. This has been noted before (Appleyard, 1969*a*; Cohen & Schuepfer, 1980), but in less controlled circumstances. In the present study, all buildings were quite similar visually, enabling us to exclude the possibility that it was mere visual distinctiveness rather than proximity to a choice point that caused certain buildings to become part of a long-term mental representation. The instructions to the subjects did not mention buildings at all, and thus did not bias the subjects to pay more than the usual attention to them. And the test itself—driving through the world and looking for changes—also differs significantly from the previous studies which used recall outside the environment. This approach makes it possible to address more detailed questions about what makes buildings into landmarks and how attention at a choice point is distributed; for example, do buildings that are on the same side of the road as a turn acquire landmarks status more often than buildings that are on the opposite side?

Recent studies on scene perception suggest that the selectivity of information pick-up is not limited to the navigational context but is a general property of the human visual system (O'Regan, 1992; Rensink *et al.*, 1997). Information pick-up is pragmatic and results from a goal-directed sensory interrogation of the environment.

Notes

Correspondence and reprint requests should be addressed to: Jack Beusmans, Cambridge Basic Research, Nissan Research & Development, Inc., 4 Cambridge Center, Cambridge, MA 02142, U.S.A.; E-mail: beusmans@pathfinder.cbr.com.

References

Appleyard, D. (1969*a*). Why buildings are known. *Environment and Behavior* **1,** 139–156.

Appleyard, D. (1969*b*). City designers and the pluralistic city. In L. Rodwin, Ed., *Planning Urban Growth and Regional Development: The Experience of the Guayana Program of Venezuela*, Cambridge, MA: MIT Press, pp. 422–452.

Appleyard, D. (1970). Styles and methods of structuring a city. *Environment and Behavior* **2,** 100–117.

Arthur, P. & Passini, R. (1992). *Wayfinding—People, Signs, and Architecture*. New York: McGraw-Hill.

Biegler, R. & Morris, R. G. M. (1993). Landmark stability is a prerequisite for spatial but not discrimination learning. *Nature* **361,** 631–633.

Biegler, R. & Morris, R. G. M. (1996). Landmark stability: studies exploring whether the perceived stability of the environment influences spatial representation. *Journal of Experimental Biology* **199,** 187–193.

Byrne, R. W. (1979). Memory for urban geography. *Quarterly Journal of Experimental Psychology* **31,** 147–154.

Cohen, R. & Schuepfer, T. (1980). The representation of landmarks and routes. *Child Development* **51,** 1065–1071.

Clarke, S., Assal, G. & de Tribolet, N. (1993). Left hemisphere strategies in visual recognition, topographical orientation and time planning. *Neuropsychologia* **31,** 99–113.

Devlin, A. S. (1976). The "small town" cognitive map: adjusting to a new environment. In G. T. Moore and R. G. Golledge, Eds., *Environmental Knowing*. Community Development Series, Vol. 23, Stroudsberg, Pennsylvania: Dowden, Hutchinson, & Ross, pp. 58–66.

Evans, G. W. (1980). Environmental cognition. *Psychological Bulletin* **88,** 259–287.

Gallistel, C. R. & Cramer, A. E. (1996). Computations on metric maps in mammals: getting oriented and choosing a multi-destination route. *Journal of Experimental Biology* **199,** 211–217.

Golledge, R. G., Dougherty, V. & Bell, S. (1995). Acquiring spatial knowledge: survey versus route-based knowledge in unfamiliar environments. *Annals of Association of American Geographers* **85,** 134–158.

Goodridge, J. P. & Taube, J. S. (1995). Preferential use of the landmark navigation system by head direction cells in rats. *Behavioral Neuroscience* **109,** 49–61.

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

Hermer, L. & Spelke, E. (1994). A geometric process for spatial reorientation in young children. *Nature* **370,** 57–59.

Hirtle, S. C. & Hudson, J. (1991). Acquisition of spatial knowledge for routes. *Journal of Environmental Psychology* **11,** 335–345.

Hirtle, S. C. & Heidorn, P. B. (1993). The structure of cognitive maps: representations and processes. In T. Garling and R. G. Golledge, Eds., *Behavior and Environment*. Amsterdam: Elsevier Science Publ., pp. 170–192.

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

Kesner, R. P., Farnsworth, G. & DiMattia, B. V. (1989). Double dissociation of egocentric and allocentric space following medial prefrontal and parietal cortex lesions in the rat. *Behavioral Neuroscience* **103,** 956–961.

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

McDonald, T. P. & Pellegrino, J. W. (1993). Psychological perspectives on spatial cognition. In T. Garling and R. G. Golledge, Eds., *Behavior and Environment: Psychological and Geographical Approaches*, Amsterdam: Elsevier Science Publ, pp. 47–82.

McNamara, T. P. (1986). Mental representations of spatial relationships. *Cognitive Psychology* **18,** 87–121.

McNamara, T. P. (1992). Priming and the constraints it places on theories of memory and retrieval. *Psychological Review* **99,** 650–662.

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.

Montello, D. R. A new framework for understanding the acquisition of spatial knowledge in large-scale environments. In R. G. Golledge and M. J. Egenhofer, Eds., *Spatial and Temporal Reasoning in Geographic Information Systems* (in press).

Moore, G. T. (1976). Theory and research on the development of environmental knowing. In G. T. Moore and R. G. Golledge, Eds., *Environmental Knowing*, Community Development Series, Vol. 23. Stroudsberg, Pennsylvania: Dowden, Hutchinson & Ross, pp. 138–164.

Moore, G. T. & Golledge, R. G. (1976). *Environmental Knowing*. Stroudsberg, Pennsylvania: Dowden, Hutchinson & Ross.

O'Regan, J. K. (1992). Solving the 'real' mysteries of visual perception: the world as an outside memory. *Canadian Journal of Psychology* **46,** 461–488.

Paillard, J. (1990). *Brain and Space*. Oxford: Oxford University Press.

Passini, R. (1984). Spatial representations, a wayfinding perspective. *Journal of Environmental Psychology* **4,** 153–164.

Piaget, J. & Inhelder, B. (1969). *The Psychology of the Child*. New York: Basic Books.

Rensink, R. A., O'Regan, J. K. & Clark, J. J. (1997). To see or not to see: the need for attention to perceive changes in scenes. *Psychological Science* **8,** 368–373.

Self, C. M., Gopal, S., Golledge, R. G. & Fenstermaker, S. (1992). Gender-related differences in spatial abilities. *Progress in Human Geography* **16,** 315–342.

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, New York: Academic Press, pp. 9–55.

Taube, J. S. & Burton, H. L. (1995). Head direction cell activity monitored in a novel environment and during a cue conflict situation. *Journal of Neurophysiology* **74,** 1953–1971.

Traverse, J. & Latto, R. (1986). Impairments in route negotiation through a maze after dorsolateral frontal, inferior parietal or premotor lesions in cynomolgus monkeys. *Behavioral and Brain Research* **20,** 203–215.

Tversky, B. (1981). Distortions in memory for maps. *Cognitive Psychology* **13,** 407–433.