Performance Models for Spatial and Locational Cognition

Perry W. Thorndyke
with the assistance of Barbara Hayes-Roth and Cathleen Stasz

Rand

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PREFACE

This report summarizes the results of a three-year investigation of human performance on tasks requiring knowledge of large-scale space. Such tasks include learning object locations and spatial relationships from a map and from navigation in the terrain, orienting oneself with respect to unseen locations, and estimating distances between objects on the map or in the terrain. The research reported here was conducted between October 1977 and September 1980 and was supported by the office of the Director of Personnel and Training Research Programs, Psychological Sciences Division, Office of Naval Research, under Contract No. N00014-78-C-0042.

The report addresses several aspects of human performance. These include the techniques that individuals use to perform the tasks, the sources of error in their performance, the abilities that influence task skill, and training methods for improving performance. Thus, the report should interest practitioners in all military service training and operational commands and analysts concerned with human skill in spatial reasoning and navigation. More detailed descriptions of the research summarized here may be found in the following companion publications:

Individual Differences in Knowledge Acquisition from Maps, by Perry W. Thorndyke and Cathleen Stasz, R-2375-ONR, January 1979.

Distance Estimation from Cognitive Maps, by Perry W. Thorndyke, R-2474-ONR, November 1979.

Training Procedures for Map Learning, by Perry W. Thorndyke and Cathleen Stasz, N-1018-ONR, July 1979.

Heuristics for Knowledge Acquisition from Maps, by Perry W. Thorndyke, N-1193-ONR, July 1979.

Spatial Cognition and Reasoning, by Perry W. Thorndyke, N-1333-ONR, April 1980.

The Influence of Visual-Spatial Ability and Study Procedures on Map Learning Skill, by Cathleen Stasz and Perry W. Thorndyke, N-1501-ONR, June 1980.

Ability and Strategy Differences in Map Learning, by Cathleen Stasz, N-1569-ONR, August 1980.

Planning During Map Learning: The Global Strategies of Individuals with High and Low Visual-Spatial Ability, by Cathleen Stasz, N-1594-ONR, December 1980.

Differences in Spatial Knowledge Acquired from Maps and Navigation, by Perry W. Thorndyke and Barbara Hayes-Roth, N-1595-ONR, December 1980.

SUMMARY

This report presents the results of a three-year investigation of the processes by which people acquire spatial knowledge and make spatial judgments in unfamiliar, large-scale environments. The research had three objectives: (1) to distinguish between the knowledge people acquire from maps and the knowledge they acquire from navigation, (2) to diagnose sources of distortion in memory representations of space and errors in task performance, and (3) to identify sources of individual differences in the spatial knowledge people acquire and the rate at which they acquire it. To meet these objectives, empirical and theoretical research examined four problems in depth: how people learn maps, how map "clutter" influences estimates of distance between points, how people learn from navigation experience, and how the accuracy of spatial judgments depends on the type of training experiences people have with an environment.

Experiments in map learning indicated that both the use of trainable, effective study procedures and visual memory ability determine success at learning a map. People with moderate and high visual memory ability significantly improved their skill at memorizing a map when given instruction on effective learning techniques. Low-ability subjects, on the other hand, did not profit from such training. These results have implications for the selection and training of Navy personnel who must learn portions of maps.

A second series of studies investigated people's procedures for and accuracy at estimating distances on "cluttered" maps—that is, maps that display information between the points of interest. These studies indicated that clutter increases subjective estimates of distance between two points, both when people use a memorized map and when they estimate while viewing the map. When subjects estimate from memory, they appear to use visual map-scanning processes similar to those they use when the map is actually present. These results indicate that map-design decisions can influence people's accuracy at using the resulting maps.

A third series of studies investigated differences in the knowledge people acquire from navigation and the knowledge they acquire from map learning. Studying a map leads to a survey, or global representation of the environment, while navigation provides a linear, or procedural representation. Each form of learning has certain advantages for spatial reasoning. Navigation experience is optimal for estimating route distances and orienting oneself toward unseen locations. Map learning is optimal for estimating the shortest distance between two points and determining relative locations of objects. These findings suggest that effective instruction about a novel environment might be enriched beyond the current practice of providing maps of the environment, particularly in cases in which navigation in the environment will be required.

ACKNOWLEDGMENTS

Several members of the Rand staff contributed to this research. Barbara Hayes-Roth, Cathleen Stasz, and Sarah Goldin collaborated with Perry Thorndyke on many of the reported studies. Frederick Hayes-Roth, Daniel Relles, and Norman Shapiro provided useful consultation throughout the course of the project. Doris McClure conducted the experiments, analyzed data, and provided programming services. Jacqueline Berman and John Burge also assisted in data analyses. Randall Steeb and David Kanouse provided valuable comments on an earlier draft of this report. Kay McKenzie prepared the manuscript.

CONTENTS

PREFACE iii

SUMMARY v

ACKNOWLEDGMENTS vii

Section

I. INTRODUCTION 1

II. REPRESENTATIONS OF SPATIAL AND LOCATIONAL KNOWLEDGE 2
- Perceptual Icons 3
- Unordered Productions 3
- Ordered Productions 4
- Symbolic Abstractions 4
- Mental Maps 5

III. DISTINCTIONS BETWEEN KNOWLEDGE ACQUIRED FROM MAPS AND KNOWLEDGE ACQUIRED FROM NAVIGATION 7

IV. INDIVIDUAL DIFFERENCES IN LEARNING FROM MAPS 10

V. INDIVIDUAL DIFFERENCES IN LEARNING FROM NAVIGATION 12

VI. DISTANCE ESTIMATION FROM LEARNED MAPS 14

VII. CONCLUSIONS 16

BIBLIOGRAPHY 19

I. INTRODUCTION

"Spatial and locational cognition" refers to the application of cognitive processes to tasks requiring the use of knowledge about large-scale space. Such tasks include learning an unfamiliar geographical region through navigation, learning a map of the region, estimating distances between locations along a straight line or along specified routes, determining the bearing of a location with respect to the current position, and selecting and navigating routes between locations.

Acquiring and using knowledge of unfamiliar terrain are skills frequently required in military situations. Pilots, soldiers in the field, and officers planning tactical maneuvers must use precise knowledge of unseen geography to carry out their operations. This knowledge often must be retrieved from memory because maps are unavailable or inefficient to use, or because operations must be carried out at night. In such cases, mission success may depend on complete and accurate memory of the terrain.

Research undertaken at Rand on the spatial and locational cognition project sought to develop cognitive models for some of the skills required to perform spatial reasoning. The project had three major goals:

1. To model the memory structures, knowledge, and processes people use to acquire and reason with knowledge about large-scale space.
2. To diagnose sources of distortions in memory and errors in performance on tasks requiring the use of spatial knowledge.
3. To identify sources of individual differences in the type of knowledge people acquire about large-scale space and the rate at which they acquire it.

Theoretical and empirical research focused on four problems, which were analyzed in depth: how people learn maps, how map "clutter" influences subjective estimates of distance between points, how people learn from navigation experience, and how the accuracy of spatial judgments depends on the type of training experiences people have with an environment. This report summarizes the project results in each of these areas and presents a set of conclusions based on the research.

The remainder of the report is organized as follows. Section II describes several types of spatial knowledge that people acquire about a large-scale space and typical sources of that knowledge. Section III describes distinctions between the performance of individuals who acquire spatial knowledge from maps and that of individuals who acquire such knowledge from navigation. Section IV analyzes differences in map-learning skill among individuals. Section V characterizes individual differences in learning from navigation. Section VI summarizes the processes people use and the errors they commit when estimating distances from cluttered maps. Finally, Section VII presents a set of conclusions and possible implications for training spatial reasoning skills.

II. REPRESENTATIONS OF SPATIAL AND LOCATIONAL KNOWLEDGE

People's knowledge of the surrounding world comes from a variety of sources, including maps, movies and photographs, verbal descriptions, and direct perceptions. Consequently, a person's spatial and locational knowledge of a particular area is typically a collection of diverse memories. These may include images of geographic features, learned sequences of actions that define specific routes, images (perhaps fuzzy) of area maps, and facts indicating relationships among objects (e.g., the distance from San Francisco to Los Angeles is approximately 400 miles).

We have postulated that spatial knowledge can be divided into three categorical types (Thorndyke, 1980; Thorndyke and Hayes-Roth, 1980): *Landmark knowledge* comprises perceptual memories of prominent geographic features in the environment, such as particular buildings, mountains, or signs. *Procedural knowledge* comprises memories of action sequences required for navigation between separate points, with object locations encoded according to their position along routes that the individual traverses. *Survey knowledge* comprises knowledge organized into map-like, global configurations of points and routes. Interpoint distances and relative locations of objects are encoded in a fixed coordinate system, rather than with respect to the position of the individual; for example, when one imagines a map of the United States, one "views" it from above and outside of the depicted space.

Within these categories, it is possible to refine the distinctions to capture differences in how detailed the knowledge is, how it is associated with related knowledge, and how it is represented. Table 1 summarizes these types of representation. A person typically has knowledge of each type about different portions of the environment. Exactly which type best characterizes his or her knowledge depends on such factors as the extent of the individual's navigation experience in the environment, the regularity of the geographic features in the environment, the person's motivation, and whether or not he or she has studied a map of the environment. Each of these knowledge types is described below.

Table 1

TYPES OF SPATIAL AND LOCATIONAL KNOWLEDGE

Knowledge Category	Form of the Memory Representation
Landmark	Perceptual icons
Procedure	Unordered productions
	Ordered productions
	Symbolic abstractions
Survey	Schematized maps
	Detailed maps

PERCEPTUAL ICONS

We refer to memory of familiar locations as *perceptual icons.* People typically acquire these icons when first encountering a new environment, such as when visiting a new city or a new area of a familiar city. As people navigate through the region, they notice various objects and encode perceptual images that capture the visual scene. Repeated experience leads to the accumulation of a data base of recognizable images. Thus, people who have spent some time in a city can look through a set of photographs and determine which buildings and locations they have seen, even if they cannot identify the relative locations of the objects or the routes connecting them.

UNORDERED PRODUCTIONS

People typically navigate through an environment toward a destination. Procedural knowledge encodes the actions required to travel between destinations in a goal-directed fashion. The simplest form of such knowledge, *unordered productions,* refers to route information that associates recognizable perceptual icons with behaviors to be performed in order to reach a certain destination. Such associations are like production rules, or situation-action pairs, of the form "if my destination is X and I am at recognizable location Y, then perform action Z." For example, the following two productions would be useful in traveling from Los Angeles International Airport to The Rand Corporation:

P1: IF the current city is Los Angeles
AND the destination is The Rand Corporation
AND the current view is the Santa Monica Civic Auditorium on the right
THEN turn right.

P2: IF the current city is Los Angeles
AND the destination is The Rand Corporation
AND the current view is Nationwide Baby Furniture on the right
THEN turn left.

The productions encoding knowledge of a route are independent; that is, they do not encode the order in which features occur along the route. Thus, there are neither explicit nor implicit associations among the productions that refer to a given route. For this reason the productions are referred to as *unordered.*

It is not unusual for a person to have extensive procedural knowledge of an environment comprising only these unintegrated route components. A person asked to give directions about a complex but frequently traveled route will occasionally say something like, "I can't tell you how to get there, but I can take you there." The difference between the ability to navigate and the ability to give directions stems from two properties of the memory representation of unordered productions. First, the productions used for navigation are independent and contain no order information. Although the person can retrieve the appropriate action associated with each of the choice points, he or she cannot retrieve the order of

arrival at the points. Second, unlike navigation, providing directions requires that a person be able to recall and explain in some detail the visual features of the locations where actions must be performed. Rules for navigation, however, depend on cued rather than uncued recall. That is, the navigator need only recognize each familiar scene and respond with the action associated with that scene. For example, a person might recognize the large white building that is the Santa Monica Civic Auditorium without knowing its name or function. Thus, while a person can recognize locations upon encountering them, he or she may not be able to name them, to generate an image sufficiently strong to be described, or to describe them in sufficient detail to enable another person to recognize them.

ORDERED PRODUCTIONS

Ordered productions extend the knowledge contained in unordered productions by including information about the sequence in which productions will be used. These sequences are encoded in associations between successive productions. Thus, the route from Los Angeles International Airport to Rand may become connected by appending to each production instructions to execute its successor. In the example given above, P2 would be modified as follows:

P2: IF the current city is Los Angeles
AND the destination is The Rand Corporation
AND the current view is Nationwide Baby
Furniture on the right
THEN turn left
AND use P1.

That is, after turning left at Nationwide Baby Furniture, the navigator should continue until he or she reaches the Santa Monica Civic Auditorium. Thus, sequential route knowledge is represented as an ordered path through a set of individual productions.

SYMBOLIC ABSTRACTIONS

As people become more familiar with the environment, they supplement their perceptual icons with knowledge about object names and approximate locations. This type of knowledge, which we refer to as *symbolic abstractions*, includes both procedural knowledge and survey knowledge.

As procedural knowledge, symbolic labels for locations may replace the perceptual information previously used for navigation. For example, one may learn that the Santa Monica Civic Auditorium is at the corner of Main Street and Pico Boulevard, so that successful navigation to Rand no longer depends on visual recognition of the building. It is necessary only to know the name of the corner at which to turn.

Symbolic abstractions may also encode survey, or configural, relations that cannot be directly perceived—for example, distances between points and their relative compass bearings or orientations. One might learn these additional facts from a map, from another person, or by computing them from direct knowledge

about routes connecting the points. This survey knowledge about relative spatial locations complements the procedural knowledge for navigating between locations. Thus, one might know not only how to travel from the airport to Rand, but also that the airport is 7 miles southeast of Rand.

MENTAL MAPS

People also represent and use survey knowledge in imaginal maps. Such representations may come from a direct encoding of a physical map in an image that preserves the spatial relations among objects on the map. Alternatively, a mental map may be constructed from numerous symbolic abstractions and from direct experience in the environment. Once a fixed coordinate system is adopted (e.g., cardinal directions), a person could, theoretically, compute relative object locations and euclidean (straight-line) distances from route distance knowledge and knowledge of compass bearings while traveling along the routes. Although people rarely make such computations and consciously store their results, it is not unreasonable to presume that as they become familiar with an environment, they adopt a canonical reference frame and learn multiple, alternative routes among points. This knowledge would be sufficient to support the continuing refinement of their survey knowledge through automatic, unconscious processes.

Whether acquired directly from a map or derived from navigation experience, mental maps are essentially visual. They are most easily acquired by individuals who have vivid visual imagery and good visual memory ability (see Section IV). Further, such imaginal maps can be examined, scanned, and manipulated in the same manner as a physical map, as discussed in Section VI.

People's mental maps vary in the amount of detail they contain. Individuals with extensive navigation experience or who have studied a map may possess nearly veridical mental maps. These are referred to in Table 1 as *detailed maps.* On the other hand, people frequently possess poorly developed maps containing normalized or oversimplified features. Such maps are referred to in Table 1 as *schematized maps.* Schematized maps often contain a simple, prototypical configuration of elements. For example, Los Angeles contains a system of streets and freeways that approximate, although differ in significant ways from, a rectilinear grid. People who have lived in Los Angeles for a short time frequently assume that most streets are parallel or perpendicular to each other. When these people draw maps of the city, they make relational errors stemming from these assumptions of regularity. Further, they are usually surprised to learn that two streets that they had assumed to be parallel actually intersect. For example, Figure 1 illustrates a map of Los Angeles drawn by a person who had lived in the area for one month. This map contains numerous normalization errors. Neither San Vicente Boulevard, Montana Avenue, nor the Santa Monica Freeway are straight thoroughfares. In fact, San Vicente and Montana intersect west of Westwood. As this person's tenure in Los Angeles increased, his maps became more accurate in their depiction of these and other details.

The distinctions between procedural and survey knowledge have important behavioral implications. In particular, the accuracy of people's spatial judgments depends on the type of knowledge they use to form those judgments and the way in which that knowledge was acquired. Section III describes the behavioral implications of acquiring primarily procedural or survey knowledge of an environment.

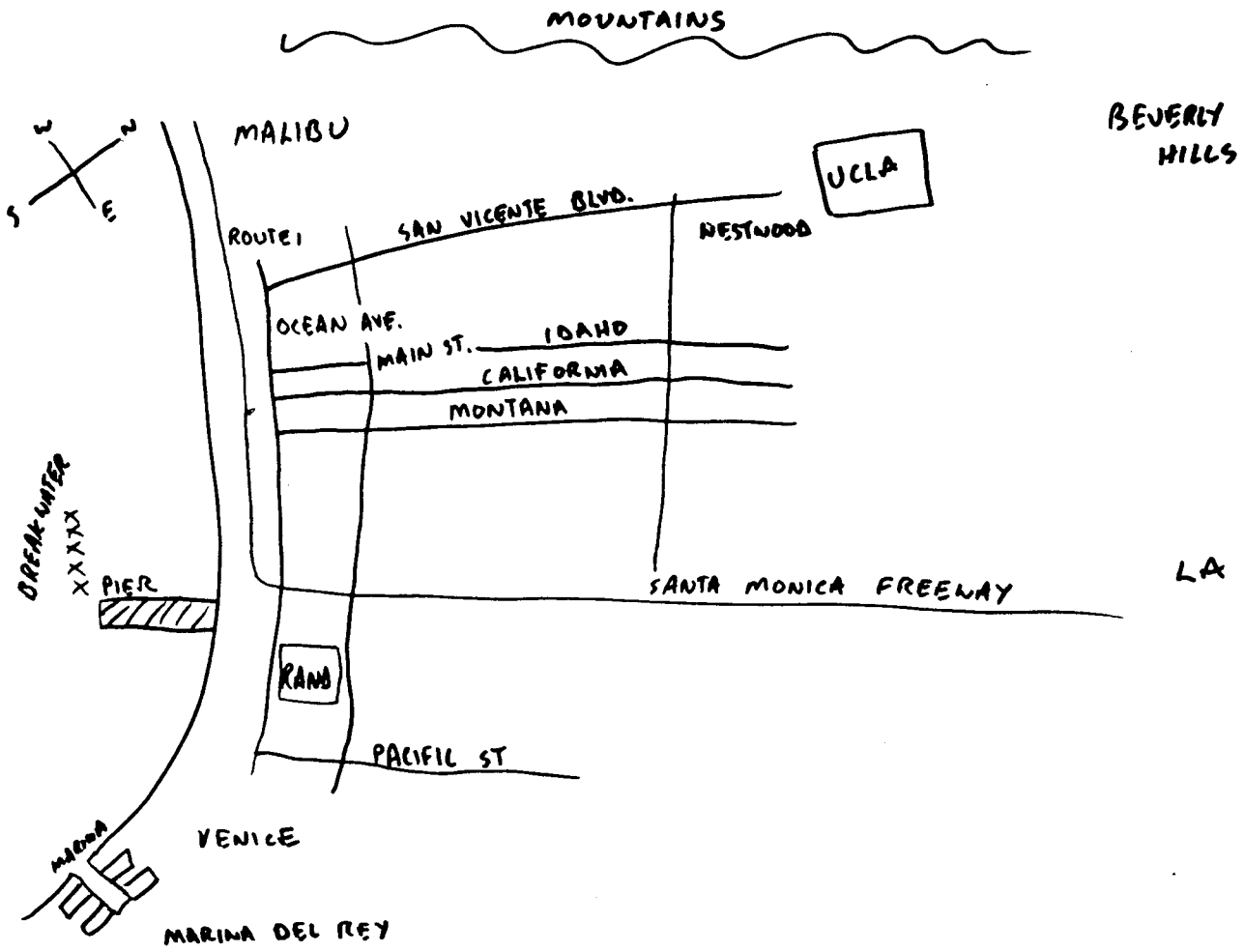

Fig. 1—A map of Los Angeles drawn by a one-month resident

III. DISTINCTIONS BETWEEN KNOWLEDGE ACQUIRED FROM MAPS AND KNOWLEDGE ACQUIRED FROM NAVIGATION

To investigate the spatial and locational knowledge people acquire from different learning experiences, we conducted a study contrasting the knowledge acquired from the two most typical sources of spatial information: maps and direct navigation experience (Thorndyke and Hayes-Roth, 1980). The goal of the study was to determine how different knowledge types influence people's spatial judgments.

Our fundamental assumption was that people acquire reasonably veridical internal representations of their experiences. Thus, people who learn from navigation should have qualitatively different memory representations from those of people who learn from a map. Experience in navigation should produce procedural knowledge of the environment, in which knowledge of the space between two points comprises the sequence of paths, turns, and sights encountered along the route connecting them. The individual's perspective on the memory representation corresponds to the canonical horizontal view he or she has of the environment during navigation. Global properties of the space, such as compass bearings of locations from other locations, are not part of the memory representation. Further, the distance between points corresponds to the distance along the route that connects them rather than the euclidean distance. Map learning, on the other hand, produces survey knowledge encoding global properties of the space, such as the size and shape of large land features and the compass bearing or straight-line direction between points. In addition, a map, and hence survey knowledge in memory derived from the map, contains both implicit route and euclidean distances. The spatial relationship between two objects is learned from a bird's-eye perspective, and the distance between them can be measured either in a direct line or along the routes connecting them.

Because these two methods of acquiring knowledge produce different internal representations, people's spatial judgments should depend on their learning experiences. People who learn from navigation must mentally simulate navigation in the environment to judge route distances. Computational procedures applied to these judgments permit them to determine euclidean distances and the orientation (i.e., direction) of objects with respect to their current location. Computing the relative locations of multiple objects in the environment (e.g., drawing a map) requires a change in perspective from a horizontal perspective to a bird's-eye perspective. Thus, navigation experience should lead to more accurate route distance estimates than euclidean distance estimates and more accurate orientation judgments (i.e., pointing in the direction of unseen objects) than relative location judgments.

In contrast, people who learn from a map can inspect their mental maps to identify the relative locations of objects. Measurement procedures permit these people to determine both euclidean and route distances between locations. Determining the orientation of an object with respect to the current location requires a change from a bird's-eye to a horizontal perspective. Thus, map learning should produce euclidean distance judgments that are at least as accurate as route dis-

tance judgments, and relative location judgments that are more accurate than orientation judgments.

In contrasting the two types of learning methods, we expected that performance should decline when a judgment requires a change of perspective or additional computation. Navigation experience, therefore, should be superior for determining orientation. Map learning, on the other hand, should be superior for making euclidean distance estimates and relative location judgments.

In addition, the *amount* of learning experience should influence the accuracy of spatial judgments. As discussed in Section II, extensive navigation experience can lead to the integration of distinct procedural segments and reorganization of the memory representation to capture survey properties of the environment. Thus, spatial judgments, which are best computed from survey knowledge, should improve as subjects accumulate additional navigation experience. On the other hand, extensive map learning should not change the nature of the memory representation, so overlearning a map should not influence spatial judgments.

To evaluate this theory and its predictions, we conducted an experiment that required subjects to make a variety of spatial judgments using their knowledge of a large-scale environment. The environment consisted of the maze of hallways and public areas in the two connected buildings of The Rand Corporation. Subjects initially learned locations and routes either by memorizing a map or by navigating in the environment. In both cases, subjects differed in the amount of exposure they had to the spatial information. Map-learning subjects varied in the amount of additional study time they were given after they had completely memorized the map. Navigation subjects were distinguished by the length of their employment at Rand: 1 month, 6 months, or 12 to 24 months. All subjects performed four types of spatial judgments: estimates of the distance between locations along hallways (route distance), estimates of the straight-line distance between locations (euclidean distance), pointing to unseen locations while standing at a particular location (orientation), and indicating the position of a particular location on a sheet of paper with respect to two given locations (object location).

The results confirmed the theoretical predictions. On all but the route estimation task, performance improved significantly with increasing navigation experience. Increasing map-learning experience did not improve performance on any task. Subjects in all navigation conditions made significantly more accurate orientation judgments than subjects with map-learning experience. Map-learning subjects performed the object location task significantly better than navigation subjects with little or moderate experience, but they performed no better than navigation subjects with extensive experience.

On the distance-estimation tasks, map-learning subjects were slightly better at judging the euclidean distance than the route distance between points. Navigation subjects, however, were in general significantly superior to map-learning subjects at judging route distances and inferior at judging euclidean distances. But subjects with extensive navigation experience were as accurate at estimating euclidean distances as were map-learning subjects.

These results illustrate three important points about spatial cognition. First, different spatial-reasoning tasks require the use of different types of knowledge. Whereas survey knowledge, for example, may be appropriate for judgments of relative location and euclidean distances among objects, it is not optimal for judg-

ments of spatial orientation. Second, different experiences induce different types of knowledge. Finally, spatial knowledge evolves and changes with extensive navigation experience. Whereas such experience initially produces primarily procedural knowledge, increasing the amount of experience induces survey knowledge that is perhaps as accurate as that obtained from learning a map.

IV. INDIVIDUAL DIFFERENCES IN LEARNING FROM MAPS

People often memorize part or all of a map to perform a variety of spatial and locational tasks, including selecting a route, navigating between points, identifying land features and objects in the terrain, and estimating distances between points. In a series of studies, we investigated the processes people use to acquire knowledge from maps (Stasz, 1980a, 1980b; Stasz and Thorndyke, 1980; Thorndyke, 1979b; Thorndyke and Stasz, 1979a, 1979b). We were specifically interested in several questions:

1. Are there large individual differences in map-learning skill?
2. What study behaviors distinguish good learners from poorer learners?
3. Can map-learning skills be successfully trained?
4. Do basic abilities predict map-learning performance?

The first experiment investigated the variety of procedures people use to learn a map and the relationship between these procedures and learning success (Thorndyke, 1979b; Thorndyke and Stasz, 1979a). We collected verbal protocols from subjects who were attempting to learn all the information on each of two maps. One map depicted a fictitious town, the other a fictitious continent.

Eight subjects participated in the experiment—three map-using "experts" (individuals who use maps frequently in their professional careers) and five "novices" (college students with no professional map-using experience). While studying the maps, subjects thought aloud about what they were looking at, how they were trying to learn the information, and how successful they thought they were.

Analysis of the protocols suggested three categories of study procedures that subjects used during learning: *attention*, *encoding*, and *evaluation*. Attentional procedures included those by which subjects selected subsets of the map information on which to focus and those by which they decided the sequence of map elements to study. Encoding procedures included techniques for holding the current information in working memory and techniques for elaborating and storing the information in long-term memory. The evaluation procedure represented subjects' assessments of whether or not they felt they had successfully learned the information on which they were currently focusing.

A comparison of the protocols of fast and slow learners revealed one or more differences in the use of procedures in each of the three categories. Good learners controlled their focus of attention on the map by isolating subsets of information and systematically learning the information in each subset before moving to a new one. Poor learners used more haphazard procedures for selecting information to learn. Good learners were more accurate in their self-evaluations of what they knew or did not know than poor learners. Further, when good learners decided that they did not yet know certain information, they were more likely to immediately attempt to learn that information. Finally, and most importantly, good and poor learners differed in the encoding procedures they used to actually learn the information on the map. Although both groups were successful at learning the verbal

information on the maps, good learners were far superior at learning the spatial information. They used a variety of techniques for learning spatial shapes and relationships, including visual imagery, encoding explicit spatial relationships between pairs of map objects (e.g., "the church is west of the fire station"), and naming a complex spatial configuration as a cue for reproduction of the shapes later (e.g., "this set of roads looks like a stick man running to the west"). In contrast, poor learners used fewer of the spatial learning procedures and were unable to learn much of the spatial information.

An analysis of the performance of experienced map users suggested that learning depended on particular procedures and not on familiarity with the task. The performance of experts ranged from the best among the eight subjects to the worst.

These results suggested that subjects' ability to impose visual organization on a map and their ability to store and retrieve visual images might influence their learning skill. Therefore, the second experiment assessed the influence of subjects' cognitive style and visual memory ability on learning performance (Stasz, 1980a, 1980b; Stasz and Thorndyke, 1980). Subjects of high and low ability but with equivalent general intelligence (as measured by tests of verbal ability, associative memory, and quantitative ability) provided protocols of their map study behavior. High-ability subjects learned the maps reliably faster and better than low-ability subjects and were more inclined to use the effective procedures identified in the first study.

Furthermore, high-ability subjects were also more inclined to adopt an overall learning strategy than were low-ability subjects. Specifically, they formed more explicit plans for focusing their study efforts and for using particular study procedures. The strategies observed among high-ability subjects included a divide-and-conquer strategy (division of the map into geographical regions and systematic study of each region), a global-network strategy (identification of a few salient features and the creation of a network of associations to these features), and a progressive-expansion strategy (systematic movement across the map from one side to the other).

The third experiment investigated the trainability of the effective learning procedures we observed in the first two studies (see Thorndyke and Stasz, 1979b). Subjects were instructed to use (a) six of the effective learning procedures we had identified previously, (b) six procedures unrelated to learning success, or (c) their own techniques. The set of effective procedures comprised three techniques for learning spatial information (visual imagery, encoding spatial relations between map elements, and encoding descriptions of isolated element shapes), two techniques for using self-generated feedback to guide subsequent study behaviors (evaluation of memory followed by study of unlearned material), and a procedure for partitioning the map into sections for study. Subjects using these procedures performed significantly better than subjects in the other groups. In addition, subjects' visual memory ability, as measured by tests of memory for complex visual scenes, predicted the magnitude of the performance differential. While high- and medium-ability subjects improved significantly after the effective-procedures training, low-ability subjects did not improve relative to the other instructional groups. Thus, both basic skills at using spatial information and the discretionary study techniques individuals employ play important roles in map-learning performance.

V. INDIVIDUAL DIFFERENCES IN LEARNING FROM NAVIGATION

Section II presented a model of several types of spatial knowledge that people acquire from navigation. The study described in Section III demonstrated several distinctions between procedural and survey knowledge and a between-subjects analysis of the effects of repeated navigation on spatial knowledge. However, since this study did not assess subjects' knowledge in the early stages of learning from navigation, we could not observe the changes in knowledge predicted by the detailed model in Section II. Further, we were interested in identifying individual differences in people's rate, style, and strategies for acquiring knowledge from navigation.

To obtain these data, we conducted an intensive study of two individuals acquiring knowledge of a novel environment in Los Angeles. These two subjects, previously unfamiliar with Los Angeles, participated in five daily learning sessions. On each day, they were driven over the same 20-mile route in West Los Angeles and instructed to learn their route and the spatial layout of the region in which they were traveling. Each day, they then completed tests of orientation, distance estimation, map drawing, location recognition, location sequencing, and route recall.

The two subjects differed in their basic abilities. DP, a male, scored high on psychometric tests of both spatial and verbal ability. JT, a female, scored high on spatial-ability tests and low on verbal-ability tests. The two individuals were equivalent on tests of associative memory and spatial restructuring.

The subjects' location recognition performance indicated the extent to which they relied on perceptual information during learning and the types of perceptual information they encoded. The stimulus materials included slides of landmarks, critical intersections (i.e., points along the route where a turn occurred), noncritical intersections (i.e., cross streets where no turn occurred), and scenes along the side of the street between intersections. We included slides of the landmarks and intersections taken from the same view the subjects encountered along the route as well as views from the opposite direction. We predicted that both subjects should learn landmarks most rapidly because of their perceptual salience. We also expected critical intersections to be learned more rapidly than noncritical intersections because the critical intersections required route-modifying actions. Finally, we expected that locational knowledge would be context-dependent—that is, that a location would be recognized much more readily when photographed from the direction in which it had been approached during learning than when photographed from the opposite direction.

Our data supported these predictions. After the first day, both subjects recognized landmarks but little else. Across days, recognition of all types of scenes improved significantly. However, landmark recognition always exceeded critical decision-point recognition, which always exceeded noncritical decision-point recognition. Further, subjects were much more likely to recognize a location photographed from the direction in which they had approached it than one photographed from the opposite direction.

The two subjects differed substantially in the type and amount of information they noticed and the learning strategies they employed. DP concentrated on verbal information, such as street names, and adopted a grid-like framework to organize his knowledge of the environment. The number of verbal labels (e.g., street and region names) included on his maps increased dramatically from day 1 to day 5. However, his recognition of decision points did not improve across the five days. In terms of the models discussed in Sections II and III, DP acquired from the outset a survey representation based on symbolic abstractions from his perceptual experiences, which he did not retain. Across days, DP's mental map expanded to include more location names but not more procedural knowledge. As discussed in Section III, survey knowledge should not improve with additional experience. Accordingly, the accuracy of DP's orientation, location, and distance judgments did not improve after day 1, even though his performance was far from completely accurate.

In contrast, JT appeared to be more perceptually oriented. She noticed landmarks and environmental features rather than the names of streets and regions. Her knowledge of street names increased more slowly than that of DP, but her recognition performance for both critical and noncritical decision points improved with experience and exceeded that of DP on all days. As JT's memory for the route improved, her ability to simulate route traversal mentally and estimate the angles of the turns along the route presumably improved. As discussed in Section III, mental simulation is the basis for spatial judgments based on procedural knowledge. Accordingly, the accuracy of JT's spatial judgments increased as her memory for the route improved. Initially, her judgments were less accurate than DP's. However, by day 5, each of JT's spatial judgments (orientation, location, route and euclidean distance) was as accurate as DP's.

These two subjects illustrate an important point introduced in the description of the map-learning experiments (Section IV): Subjects with different abilities bring different strategies to bear in spatial-learning tasks. These strategies, in turn, influence both the type of knowledge acquired and its accuracy.

VI. DISTANCE ESTIMATION FROM LEARNED MAPS

In Section III, we postulated that subjects perform spatial judgments from learned maps by inspecting and measuring a visual image. It is well-documented in psychological studies of perception that a filled or "cluttered" space between two points appears to be longer than an equal but uncluttered space. We conducted a series of experiments to investigate the possible relationship between this clutter phenomenon and subjects' distance estimates from learned maps (Thorndyke, 1979a). We were particularly interested in how subjects compute their estimates and how map clutter might distort those estimates.

In Experiment 1, two groups of subjects viewed a map containing a network of roads and cities. One group was explicitly instructed to learn the map so that they could accurately redraw it. The other group was instructed to learn the neighbors of each city. The map was then removed, and subjects were asked to estimate the distances among various pairs of cities. Subjects' estimates of the distance between points increased significantly with the number of intervening points along the judged route.

In Experiment 2, different subjects studied the same map to learn the exact locations of the cities on the roads. When these subjects estimated distances from their memorized maps, estimates increased as a linear function of the number of intervening points along the route.

In Experiment 3, subjects estimated distances while viewing the map. The effect of clutter was reduced but not eliminated. Estimates still increased linearly and reliably with clutter, but the slope of this function was smaller than in Experiment 2.

The first three experiments used artificial maps as experimental stimuli. In Experiment 4, subjects estimated distances between large U.S. cities both from memory and while viewing a map of the United States containing no state outlines. When subjects estimated distances from memory, both the number of intervening cities and the number of intervening states increased their distance estimates, indicating that people's cognitive maps of the United States organize cities within states. As demonstrated in earlier studies, the judged distance across major boundaries is longer than the same distance perceived within a region. In contrast, when subjects estimated distances while viewing a map with cities but without state outlines, only intervening cities distorted subjects' estimates.

The results of these experiments demonstrate the similarity between perceptual and memorial processes of distance estimation. Several models for the process by which subjects arrive at their estimates were formulated and fit to the data from Experiments 2 and 3. The model providing the best fit to the data was the Linear Scanning Model. This model assumes that a subject estimating the length of a route perceptually scans the route (when viewing the map) or an image of it (when judging from memory). When the subject begins the scan from the start point of the route, an internal clock, or timer is activated. At each intervening point along the route, the subject stops the visual scan, retrieves the name of the city, and compares it with the name of the destination point. If the names do not match, the scan continues to the next city. This processing requires additional time, thus

increasing the overall scan time. When the destination point is reached and verified, the timer is deactivated and the cumulative time is converted into a mileage estimate based on the scale provided on the map.

The scanning process and the operations required to test intervening points are assumed to be independent, so their contributions to the overall decision time and hence the judged distance are additive. Since the effect of intervening points is independent of the actual distance to be estimated, the proportional increase in estimates due to clutter decreases with increasing distance. That is, the longer the distance to be estimated, the smaller the relative effect of intervening points on the estimate. This seems intuitively reasonable, since, for example, when the line to be estimated is very long, a single intervening point produces a negligible effect.

VII. CONCLUSIONS

The research summarized in this report suggests the following conclusions regarding human acquisition and use of spatial and locational knowledge.

1. *People encode several types of spatial knowledge in memory.* Spatial representations comprise a complex set of facts, images, actions, and procedures. Some of this knowledge, such as the appearance of landmarks and procedures for navigating between points, can be obtained directly in the environment. Other knowledge, such as distances between points and their relative locations, must be computed from the products of experience or obtained from a map. Many factors influence the knowledge that a person has about an environment. We have documented the effects of several of these factors, including type of experience with the environment, amount of practice, strategies and procedures used to acquire the knowledge, and the visual and spatial abilities of the learner.

2. *Different instructional methods produce different types of knowledge.* Our studies of subjects learning a new environment illustrated that map learning leads to two-dimensional, bird's-eye knowledge of configural properties of the environment (survey knowledge). Navigation experience, on the other hand, leads to three-dimensional, procedural knowledge of routes and locations.

3. *Task performance depends on the quality of the knowledge representation.* Knowledge "quality" subsumes several factors, including amount of available knowledge, the form of the representation (procedural or survey), and the available processes for acquiring and using the knowledge. For some tasks, procedural knowledge leads to optimal performance. For other tasks, survey knowledge leads to optimal performance. The training of spatial knowledge for task performance must take into account the nature of the target task to be performed.

4. *Spatial tasks performed in memory frequently depend on perceptual processes.* We have studied a variety of tasks in which subjects use perception-like processes in memory. In map-learning studies, we observed that successful subjects use imagery to encode map information and that subjects with low visual memory ability have difficulty learning maps. In distance-estimation studies, we found that subjects scan a learned (mental) map and make errors in the same way they scan and err when using a hardcopy map. In a study contrasting navigation learning and map learning, we found that subjects who had learned a map inspect and perform measurements on their learned maps to compute a variety of spatial judgments.

These results may have important policy implications for the future design of maps, particularly computer-generated graphic displays. Many maps are difficult to use because they are overcrowded with data. Designers of dynamic, computer-generated maps of the future should therefore consider the desirability of presenting geographic displays that supply requested information but minimize the amount of task-irrelevant data. Such request-driven displays could provide the information users need without introducing errors caused by overly cluttered images.

5. *Individuals differ in preferred knowledge representations and available processes.* Our studies of knowledge acquisition from maps and from navigation showed that subjects of differing abilities vary in the learning procedures they use

and in their success at learning. Such differences may interact with the preferred knowledge representation used to perform a task to produce systematic differences in performance. From a selection standpoint, individuals with high visual-spatial ability may be best suited to perform tasks requiring memorizing or visualizing maps. The knowledge required for task performance may often be represented in alternative ways. One type of representation may be optimal for a person with high visual-spatial ability, another for a person with low visual-spatial ability. If performance depends on matching the knowledge representation to individual abilities, it is important to tailor instructional techniques to the skills of the learner.

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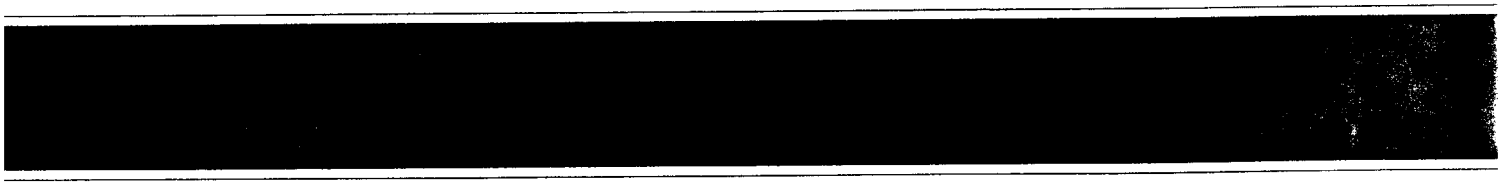
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