SPATIAL ANALYSIS OF COGNITIVE MAPS

Yoshiki WAKABAYASHI

Abstract This paper presented an integrated framework for the quantitative analysis of the spatial patterns in cognitive maps by connecting the procedures of spatial analysis to the cognitive mapping process. The author applied this framework to an empirical analysis of the data derived from the students in four Japanese cities dividing the components of distortions into the absolute and the relative ones.

The absolute distortion was analyzed by handling the data derived from sketch mapping in Hiroshima and Kanazawa. The cognitive directions in these cities deviated systematically from the actual ones so as to adjust the reference lines, namely the river channels, to cardinal directions; cognitive distances tended to be overestimated. These facts were entirely explained by rotation/alignment heuristics and implicit scaling model.

The sketch maps and distance estimates in Tokyo and Sapporo were analyzed in terms of the relative distortion. The cognitive maps for three sample groups in Tokyo commonly showed a transformation of the Yamanote Line to a well-balanced form in a similar manner to the result obtained by Canter and Tagg (1975). This supports the reliability of the method used to extract the cognitive maps. As for the validity of the method, the subjects' self-evaluation of their cognitive maps indicated that sketch mapping is superior in criterion-related validity.

The cognitive maps in Sapporo indicated a somewhat different tendency in the methods for extracting them: the sketch maps showed a striking similarity with the actual map, but the configurations recovered from distance estimates were closely related to the route-distance space. This tendency implies a non-Euclidean property of the cognitive map, which was also validated by the stress values of MDS being lowest for the city-block metric among three Minkowskian metrics. Another component of errors in cognitive maps, called fuzziness, was measured by standard deviational ellipses for each locations. The fuzziness of locational cognition was greater in peripheral places than in central ones within the study area.

The information-processing model provided us with an comprehensive explanatory framework for these spatial patterns in cognitive maps. Although it gave a satisfactory explanation of the patterns of distortions, those of fuzziness were hard to explain.

Key words: cognitive map, MDS, Euclidean regression, information-processing model, Japanese cities

1. Introduction

Whenever people plan and execute movement in an environment, they must possess cognitive representations of that environment, called cognitive maps, that are similar in function to the actual map. The cognitive map is also recalled and altered when they communicate spatial information with others (*e.g.*, way-guidance, geographical education). Thus, the cognitive map is indispensable for their everyday life.

Cognitive map have been the focus of a considerable amount of research in psychology, architecture and computer science as well as geography including cartography, although their viewpoint and methodology varies with the fields. In approaching cognitive maps, geographers can contribute to the progress of this interdisciplinary collaboration in at least two aspects. First, employing the techniques of spatial analysis and cartographic projection, they can graphically represent and quantitatively analyze the cognitive map. This enables us to visualize the state of the cognitive map and to evaluate its properties objectively. Second, geographers can explain the nature of the spatial patterns of cognitive maps by considering the characteristics of the physical environment that have usually been neglected in other fields. Thus, they could contribute to designing a safe and comfortable city by running a diagnostic check on the physical environment in terms of legibility and imageability (Lynch, 1960).

Studies of cognitive maps also play important roles within geography. First, understanding the cognitive map as a source of the decision-making process is indispensable for the explanation of spatial behavior, which has been the major aim of behavioral geography. In addition, it will afford a better understanding of the man-environment relationship that has been a long-standing theme in geography. Second, cognitive maps play an important role in the process of cartographic communication which has become a new theme handled recently by cartographers. Specifically, the findings about the nature of cognitive maps will be useful for designing an effective map in cartographic communication. From a different point of view, graphical representations of cognitive maps may be regarded as a new type of thematic maps (Wakabayashi, 1989a). Third, findings regarding the cognitive processing of spatial knowledge are applicable to geographical education and GIS (Geographic Information Systems).

The purposes of the present study are to analyze quantitatively the spatial patterns of cognitive maps using the techniques of spatial analysis and to explain them on the basis of the information-processing model. To achieve these aims, the concept of cognitive map and the previous studies in geography are briefly reviewed to raise several problems in the subsequent chapter. Then, an integrated procedure for analyzing the spatial patterns of cognitive maps is presented in Chapter 3. This is followed by an analysis of the data collected in four Japanese cities. In Chapter 5, the author discusses the factors affecting the distortions in cognitive maps on the basis of an explanatory framework of information-processing model.

2. Background and Aims

The concept of cognitive map

Tolman (1948) devised the term "cognitive map" as a hypothetical construct so as to demonstrate that the rat latently forms a map-like representation through running about a maze. That is to say, he intended the term as a figurative expression of the environmental representation supposed to be stored in the rat's brain. Accordingly, it should be noticed that the cognitive map does not necessarily have the same form as the cartographic map (Downs, 1981a). Since the cognitive map originally bore such a metaphorical meaning, the term has caused much misunderstanding and confusion. For example, Graham (1976 and 1982) criticized the relevance of the idea of mental (or cognitive) map based on the misunderstanding that the mental (or cognitive) map has a real existence like the cartographic map. Downs (1981a, b, c) argued against Graham, emphasizing that the cognitive map is only a convenient metaphor even if its real existence is not yet known.

Hesse's (1970, p. 157) view that "theoretical explanation as metaphoric redescription of the domain of the explanandum" supports the relevance of such a figurative expression as the cognitive map even in scientific research. Specifically, analogical thinking about the cognitive map has the following two significant functions in scientific research: the persuasive function of affording a better understanding by comparing a lesser-known thing to a well-known one, and the discovery function of elucidating some latent properties of the research object. Hence, the geographical approach that draws an analogy between cognitive and cartographic maps could contribute to bring us a better understanding of the nature of cognitive maps and to uncover their unknown properties.

Turning now to recent trends in cartography, remarkable progress in remote sensing and computer mapping requires reconsideration of the concept of the "map" itself. As a result, ICA (International Cartographic Association) has organized "Working group on the concept and methodology of cartography" (Kanakubo, 1991). In addition, Moellering (1980) attempted a comprehensive classification of maps, in which the cognitive map is categorized as a virtual map. Considering such a change in the concept of the map itself, comparison between cognitive and cartographic maps may become irrelevant. The remainder of the paper adopts the following definition of cartographic map given by Robinson *et al.* (1978, p. 4): first, the representation is dimensionally systematic in that there is a definable mathematical relationship among the objects shown; secondly, it is usually made on a flat surface; thirdly, it can show only a selection of geographical phenomena that have been somehow generalized.

Concerning the cognitive map, the following definition by Downs and Stea (1973, p. 9) has until now been widely accepted: the product of cognitive mapping that is a process composed of a series of psychological transformations by which an individual acquires, codes, stores, recalls, and decodes information about the relative locations and attributes of phenomena in his everyday spatial environment. Furthermore, they divided the information contained in cognitive maps into the locational and attributive information. Previous studies mainly dealt with the former, while only a few attempts were systematically made at the latter. The present study is not concerned with the latter aspect of the cognitive map but focused upon the nature of the former to explore its spatial properties.

While Downs and Stea (1973) suggested a functional similarity between the cognitive and the cartographic maps, they mentioned nothing about the form of the cognitive map. Its form depends on whether it is the internal representation in the head or the external one directly observed by others. According to the physiological studies, the cognitive map as an internal representation is believed to be contained in the hippocampus which provides organisms with an a priori Euclidean spatial framework (O'Keefe and Nadel, 1978). By contrast, whether it is directly made by the subject or indirectly reconstructed by the researcher, the external representation is a product of the internal one and expresses some aspects of the subject's environmental cognition in a map-like form.

Liben's (1981) distinction among three levels of spatial representations is useful for indicating the relationship between the internal and the external representations (Lloyd, 1989, p. 104). She called spatial information stored as implicit or tacit knowledge in the head "spatial storage." The second type of representation, "spatial thought," refers to thinking that concerns or makes use of space in some way. The cognitive map as an internal representation corresponds to these two types. The third type of them called "spatial product" is considered to be external products that represent space in some way, containing the cognitive map as an external representation.

Previous studies and their problems

As mentioned above, geographical studies about the cognitive map are mainly characterized by the comparison of the cognitive map to the actual one. Nevertheless, remarkable progress in related fields influenced them and brought about some change in it. Development of geographical studies can be roughly divided into the four periods according to their methodological changes: in the 1960s, the qualitative analysis of sketch maps prevailed; in the early 1970s, quantitative analysis of sketch maps and cognitive distances advanced; in the late 1970s, the application of MDS (Multidimensional Scaling) afforded new techniques for dealing with the spatial properties of cognitive maps; and in the 1980s, systematic attempts to explain the distortion in cognitive maps applying the theories of cognitive science have been made.

Kevin Lynch's work (Lynch, 1960) is well-known for being the first attempt to clarify the image of the city using sketch maps, though he enquired little into the spatial properties of cognitive maps. Their spatial patterns were dealt with by Appleyard (1969) who established a criterion for classifying cognitive maps into topological/positional and sequential/spatial. This classificatory criterion has been adopted in subsequent studies (*e.g.*, Goodchild, 1974; Pocock, 1976). Nevertheless, these works remained qualitative analyses of sketch maps.

In the 1970s, the quantitative analysis of cognitive distance, first undertaken by Thompson (1963), produced some useful findings (Pocock, 1978; Okamoto, 1982). Most of them have focused upon the functional relationship between the cognitive and the actual distances. They also dealt with the factors influencing cognitive distance dividing them into the subject-centered, the stimulus-centered, and the subject-stimulus-centered ones (Briggs, 1976; Okamoto, 1982).

Another spatial component of the cognitive map is cognitive direction. Trowbridge

(1913) turned attention to cognitive direction in his seminal work on the cognitive map, pointing out that its systematic error is affected by the frame of reference in geographic space. However, farther investigation into it has never been made by geographers except for Pocock (1972), Takahashi (1972) and Cadwallader (1977).

Even if cognitive distance might be an important component of the spatial properties of cognitive maps, it is evident that one-dimensional analysis of cognitive distance can hardly grasp the entire properties of cognitive space. To elucidate these properties, Golledge *et al.* (1969) initiated a spatial analysis of the cognitive map applying MDS to the matrix of cognitive distances. In the 1970s, systematic studies of cognitive maps using MDS were carried out mainly by the groups of R.G. Golledge and D.B. MacKay in United States (Sugiura, 1985 and 1990). This methodology enables us to examine quantitatively the spatial properties of the cognitive map, such as their non-Euclidean nature and dimensionality.

Naturally, some method for quantitative comparison between the cognitive configuration recovered by MDS and the actual one was necessary to grasp the spatial properties of cognitive maps. Although early studies performed this by the heuristic transformation of coordinates, the automated procedures (*e.g.*, CONGRU and EUCLID) were developed in the 1980s for analyzing the cognitive configuration. These procedures contained Euclidean regression and bidimensional statistics. While a large number of quantitative analyses of the spatial patterns in cognitive maps were attempted mainly in the United States, consistent explanations of the empirical facts obtained by them had never been given.

After the 1980s, a consistent framework for explaining the process of cognitive mapping was developed owing to rapid progress in cognitive science. Lloyd (1982) introduced the theories of cognitive science to the geographical studies of environmental cognition. Since then, he carried out some empirical studies (Lloyd and Heivly, 1987; Lloyd, 1989) of the distortions in cognitive maps to establish an explanatory framework for cognitive mapping on the basis of the information-processing model. Moreover, *Geoforum* recently published a special issue concerning the cognitive map (*Geoforum*, 23-2, 1992), where the editor planned to call geographers' attention to cognitive science.

In this way, geographical studies of cognitive maps shifted their emphasis from measurement of their distortions to exploration of their formation process. Recently, studies of the process of cognitive mapping have become split into the behavioral approach which concerns direct experience through navigation (*e.g.*, Golledge *et al.*, 1991 and 1992) and the cartographic approach treating indirect experience through cartographic media (*e.g.*, Lloyd, 1989; MacEachren, 1992), although the information-processing model of cognitive science affords a common basis for these two approaches. In addition, recent studies of cognitive maps also dealt with the following divergent themes: the application of cognitive maps to the development of GIS or navigation systems (Peuquett, 1988; Fujita *et al.*, 1990), the comparison of cognitive mapping between normal and special populations (Golledge, 1991), and the examination of gender-related differences in spatial abilities (Self *et al.*, 1992).

Consequently, geographical studies of cognitive maps have become incorporated into the multidisciplinary collaboration among the cognitive sciences. Such a tendency entails the danger of making the geographical studies dissolve into part of cognitive science (Gold, 1992). Even though it is necessary for such research to promote communication among different fields, it also becomes increasingly important that the geographers involved in an interdisciplinary research do not forget their own specialty. As mentioned above, a role of the geographical approach is to compare the cognitive map with the actual one by employing the methodology of spatial analysis and cartography as well as to explain spatial behavior. In other words, a notable feature of the geographical approach is to compare the internal process of cognitive mapping to an external process of cartographic mapping (Fig. 1).

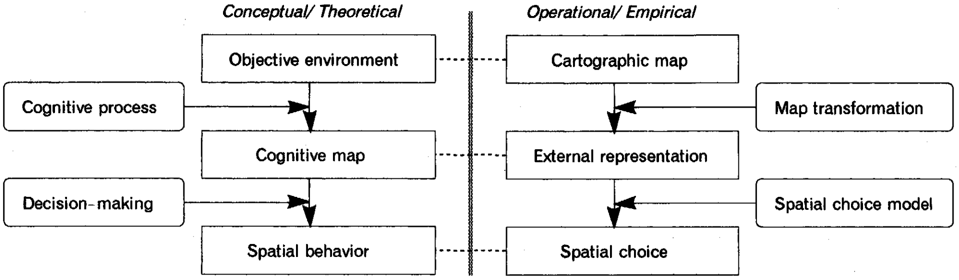


Fig. 1 An analytical framework for the geographical studies of cognitive maps

Until now, a great deal of effort has been made in the cognitive process, detecting some spatial properties of cognitive maps. Nevertheless, more detailed research about the following questions is necessary: How can we represent and measure the cognitive map in order to compare it with the actual one ?; How different is the spatial patterns in cognitive maps from those of the actual one ?; Why are they so different from each other ? These questions will be handled in the subsequent chapters.

3. Methodologies for Analyzing Spatial Patterns in Cognitive Maps

Methods for extracting cognitive maps

The methods for extracting and representing cognitive maps are classified into the following two types: direct mapping that asks subjects to reproduce externally the cognitive map in map-like forms; indirect mapping by which the researcher reconstructs external representations in accordance with the response of subjects.

The direct mapping includes the techniques of drawing maps on a sheet, board or CRT (*e.g.*, Lynch, 1960; Sherman *et al.*, 1979; Baird *et al.*, 1979; Richardson, 1981b) and the cloze procedure (*e.g.*, Robinson and Dicken, 1979). Indirect mapping refers to various techniques, such as distance estimation, record of reaction time, and the analysis of verbal protocols (Siegel, 1981; Siegel and Cousins, 1985). Most of the previous studies used sketch mapping and distance estimation because they are easily compared with the actual map. However, it seems that each technique has advantages and disadvantages.

Sketch mapping assumes that locations of points on a hand-drawn map reflect their counterparts on the cognitive map. It demands of the subjects less abstract and more natural tasks and is able to obtain more consistent data due to a visual feedback during the task than distance estimation (MacKay, 1976, p. 441; Buttenfield, 1986, p. 239). However, it also has some disadvantages. First, its results depend upon the subject's map-reading experience and drawing ability (MacKay, 1976, p. 440; Magana *et al.*, 1981, p. 294). Second, the amount of time put into the task influence the results (Day, 1976, p. 196). Third, the size of the drawing paper and the locations of the first few points will restrict the task (Day, 1976, p. 196). Finally, unconstrained mapping produces highly irregular results (Buttenfield, 1986, p. 239).

The above disadvantages can be avoided using distance estimation. This technique is used in various ways such as verbal estimation, direct distance estimation, ratio scaling and paired comparison procedure (Day, 1976), so that it is applicable to a wide range of settings. In addition, if coupled with MDS, distance estimation becomes more objective and replicable than sketch mapping (Buttenfield, 1986, p. 239).

MDS was originally devised by psychologists as a method for the spatial representation of structure in data. It enabled geographers to make a spatial analysis assuming the relativity of distance metrics (Sugiura, 1985). Although there are a variety of algorithms of MDS, all share the common characteristics (Golledge, 1977). First, they are based on the assumption that there is a monotonic relation between interpoint distances and data. Second, they use an iterative procedure of adjusting coordinates for points in order to achieve a closer approximation to the desired monotonic relation. Third, they yield spatial representations of data. The algorithms of MDS are classified into metric and nonmetric ones according to whether the measurement scale of input data is on a ratio/interval scale or ordinal scale. Most of the previous studies have used nonmetric MDS that permits various methods of data collection (Sugiura, 1985 and 1990). Nonmetric MDS is suitable for uncovering the latent properties of cognitive maps because its type of input data is suited to cognitive data; besides, it permits one to handle non-Euclidean distances within Minkowskian metrics.

However, this method also has some disadvantages. First, it assumes subjects to be equally familiar with all the given locations. Second, the MDS algorithm will introduce some geometric bias into the result (Buttenfield, 1986, p. 239). Third, it demands of subjects more abstract and less natural tasks than sketch mapping (MacKay, 1976, p. 441).

Accordingly, the answer to the question which technique should be used will vary with the criterion of validity. In terms of conceptual validity, distance estimation seems superior to sketch mapping because the former is not necessarily based on an assumption of the latter that the internal representation has two-dimensional Euclidean properties. Concerning the empirical validity, however, the superiority will depend on research conditions. For instance, distance estimation can be valid in asking blind people, while sketch mapping might be fit for young children (Buttenfield, 1986, p. 240). Although several studies have already dealt with the empirical validity of these techniques (*e.g.*, MacKay, 1976; Baird *et al.*, 1979), little is known about its relationship to conceptual validity. Therefore, the author examines the validity as well as the reliability of these two techniques by relating their results to the explanatory framework of the cognitive-mapping process.

Components of distortions and methods for measuring them

The distortion in cognitive map is defined in geometric terms as the displacement of locations between the cognitive and the actual maps. Some transformation of the two maps into the same coordinate system is necessary to measure it. This is easily performed by employing the techniques for computer image processing. Although there are many procedures for coordinate transformation such as Euclidean regression (Tobler, 1983; Wakabayashi, 1991), an important issue in exploring the properties of the cognitive map is whether any substantial meanings can be attached to the procedure in connection with the cognitive process. In this respect, Lloyd (1989) drew an useful distinction between the absolute and the relative distortions. The definition of systematic distortion and fuzziness given by Gale (1982) is also relevant to statistical analysis. In this chapter, the author examines these components of distortions relating their formal meanings in geometry and statistics to their substantial ones in cognitive science.

Absolute and relative distortions

According to Lloyd (1989), transformation of cognitive maps into the same coordinate system as the actual map employing Euclidean regression is equivalent to the task of separating the absolute distortion from the relative one. The absolute distortion refers to systematic error caused by cognitive processes, which translate, rotate and scale locations. Among these transformations, translation and rotation are assumed to be a product of perceptual organization given the name of alignment and rotation heuristics (Tversky, 1981), which simplify the cognitive map by rotating it to align with a cardinal direction. Scaling can be due to a decoding process referred to as implicit scaling (Holyoak and Mah, 1982) that expands space around reference points. By contrast, the relative distortion cannot be removed by such systematic transformations, being difficult to explain via general theories (Lloyd, 1989, pp. 105-106).

Operationally, the absolute distortion is detected by coefficients of Euclidean regression (Tobler, 1965) applied to the cognitive map. Here, the form of the Euclidean regression can be written as follows:

$$\begin{pmatrix} u_i \\ v_i \end{pmatrix} = \begin{pmatrix} a_1 & -a_2 \\ a_2 & a_1 \end{pmatrix} \begin{pmatrix} x_i \\ y_i \end{pmatrix} + \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} + \begin{pmatrix} e_i \\ f_i \end{pmatrix} \qquad 1 \leqq i \leqq n, \tag{1}$$

where (u_i, v_i) and (x_i, y_i) denote the locations of point i on the actual and the cognitive maps respectively, (e_i, f_i) is residual matrix, and a_1, a_2, b_1, b_2 are parameters. By defining $c = \sqrt{a_1^2 + a_2^2}$ and $\theta = \cos^{-1}(a_1/c) = \sin^{-1}(a_2/c)$, we can rewrite Eq. (1) as

$$\begin{pmatrix} u_i \\ v_i \end{pmatrix} = c \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x_i \\ y_i \end{pmatrix} + \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} + \begin{pmatrix} e_i \\ f_i \end{pmatrix}, \tag{2}$$

where b_1 and b_2 are indices of horizontal and vertical translations respectively, c refers to scale change, and θ denotes the angle of counterclockwise rotation. The relative distortion is indicated by (e_i, f_i), which refers in geometric terms to the discrepancy between the cognitive map transformed by Euclidean regression and the actual map.

To measure the absolute distortion in this way, however, the configuration of the cognitive map before transformation is necessary to have the same coordinate system as the actual map. If its scale, direction, and origin do not correspond with those of the actual map, as is often the case with the output of MDS, the parameters in Eq. (2) cannot indicate the degree of absolute distortion. Hence, at least two reference points in cognitive maps have to be prespecified so as to correspond with the coordinate system of the actual map.

Some parts of orthogonal Procrustes rotations are equivalent to Euclidean regression because both of them perform Euclidean transformation based on the criterion of least squares. Procrustes rotation was originally devised for comparing two sets of factor loadings by orthogonally rotating them to maximum congruence (Shiba, 1979). Schönemann and Carroll (1970) improved it to perform reversion as well as Euclidean transformations. An outline of this procedure is as follows (Takane, 1980):

Let $\boldsymbol{Y}$ and $\boldsymbol{X}$ be coordinate matrices of the actual and the cognitive maps respectively, transformations for fitting $\boldsymbol{X}$ to $\boldsymbol{Y}$ with translation, orthogonal rotation, and scale change are given by

$$\boldsymbol{Y} = \mathrm{c}\boldsymbol{XT} + \boldsymbol{1a}' + \boldsymbol{E}, \tag{3}$$

where $\boldsymbol{T}$ is rotation matrix, c is the scalar for scaling, $\boldsymbol{a}$ is translation vector, $\boldsymbol{E}$ is residual matrix, and $\boldsymbol{1}' = (1, 1, \ldots 1)$. Under the condition that $\boldsymbol{T}$ is orthogonal matrix, $\boldsymbol{T}$, $\boldsymbol{a}$ and c will be obtained by minimizing the sum of squares of residual $\boldsymbol{E}'\boldsymbol{E}$. For further details of this procedure, see Takane (1980) or Schönemann and Carroll (1970). Although its derivation process and algorithm are somewhat different from those of Euclidean regression, both of them produce the same results if $\boldsymbol{X}$ and $\boldsymbol{Y}$ are standardized to fit their mean centers into the origin of the coordinate system.

However, Euclidean regression possesses some defects compared with Schönemann and Carroll's procedure. First, ordinary Euclidean regression cannot perform reversion. Secondly, Euclidean regression is applicable to only two-dimensional configurations, while Schönemann and Carroll's procedure can deal with higher dimensional ones. Yet, these defects are overcome by improving some parts of its procedure (Wakabayashi, 1989b, p. 344). On the other hand, since Euclidean regression was devised on the basis of an analogy between unidimensional and bidimensional variables, it affords some extensions to non-Euclidean regressions (Tobler, 1983).

The discrepancies between the cognitive and the actual maps remained after this transformation exhibit relative distortions. The following measures of these discrepancies were used in previous studies: bidimensional correlation (Golledge, 1978a, b; Richardson, 1981a, b), Cliff's (1966) ϕ, product-moment correlation of interpoint distances, mean cosine of the angles between equivalent points (MacKay *et al.*, 1975; Olshavsky *et al.*, 1975; MacKay, 1976), and distortion index (Waterman and Gordon, 1984; Lloyd, 1989). Wakabayashi (1989b) made comparison between these measures applying three of them to the same data. He concluded that bidimensional correlation was congruent with the other measures proving it to be a typical measure of the relative distortion. In addition, Waterman and Gordon's (1984) distortion index, Cliff's ϕ and its revision of Lingoes and Schönemann (1974) are derived from bidimensional correlation because these measures are based on the criterion of least squares in common (Wakabayashi, 1991). Accordingly, the present study adopts bidimensional correlation as an overall measure of relative distortions. Bidimensional correlation is defined here as:

$$R = \sqrt{1 - \frac{\sum_{i=1}^{n}(u_i - \hat{u}_i)^2 + \sum_{i=1}^{n}(v_i - \hat{v}_i)^2}{\sum_{i=1}^{n}(u_i - \bar{u})^2 + \sum_{i=1}^{n}(v_i - \bar{v})^2}}, \tag{4}$$

where (u_i, v_i) and $(\hat{u}_i, \hat{v}_i)$ denote the location of the point i on the actual map and that of the cognitive map fitted to the actual one respectively, $(\bar{u}_i, \bar{v}_i)$ is mean center of locations on the actual map, and n is the number of points (Gatrell, 1983, p. 97). The value of R varies between 0.0 to 1.0, with 1.0 indicating perfect fit. This measure is analogous to the ordinary correlation coefficient because it represents in statistical terms the ratio of explained variance to total variance. In geometric terms, numerator and denominator of the right side of the Eq. (4) indicate the sum of the squares of the distance between corresponding locations and that of the distance from mean center to each location respectively. Therefore, we can assess the relative discrepancies between the cognitive and the actual maps by using this measure.

Distortion and fuzziness

Discrepancies between the cognitive and the actual maps seem to consist of two distinct components: common component among subjects, and the peculiar one that is associated with variability among individuals. Gale (1982) called the former "distortion or accuracy" and the latter "fuzziness or precision" according to Tobler (1976). These components correspond with Lloyd and Heivly's (1987) distinction between systematic distortions and mistakes. Specifically, systematic distortions are the result of normal cognitive processing and complete information, so that they occur on aggregated cognitive maps. Mistakes are caused by incorrect or incomplete information, so that they occur on individual cognitive maps.

Aggregation of cognitive maps over all subjects employing standard deviational ellipses can separate these components operationally. According to Gale (1982), the displacement between the mean center of locations in cognitive maps and the actual location refers to accuracy or distortion; axis or shape of the standard deviational ellipse refers to precision or fuzziness. In statistical terms, such a displacement refers to errors, which are divided into systematic and random ones. Assuming that the locations in the actual map give "actual values," the systematic and the random errors correspond to distortion and fuzziness respectively. However, this conceptualization is irrelevant unless the subjects were sampled from a homogeneous population.

The above definitions and meanings of the components of distortions are summarized in Table 1. In consequence, the distinction between the absolute and the relative distortions is based on their geometric nature, while the separation of distortion from fuzziness is associated with their statistical properties. The present study mainly focuses on the geometric aspect of the distortion.

Table 1 Operational definitions of the component of distortions in cognitive maps

Geometric transformation	*Statistical aggregation*	
	Distortion	Fuzziness
Absolute distortion	Average values for the coefficient of Euclidean regression	Variation in the coefficient of Euclidean regression
Relative distortion	Displacement of mean center of the cognitive location from the actual location	Standard deviational ellipses for the scatter of cognitive locations

Study areas and data

Study areas

The study was carried out in the following four cities: Hiroshima, Kanazawa, Tokyo, and Sapporo. These cities were chosen as their physical environment affords marked contrast to each other.

The landscape of Hiroshima is characterized by six tributaries of the Ohta River running through the built-up area from north-east to south-west (Fig. 2). The central part of the city lies on a deltaic plain, where the street system gives a grid pattern. The directions of the streets deviate 10 or 30 degrees clockwise from the cardinal directions, paralleling the river channels.

The urban area of Kanazawa is also separated by the two major channels of the Sai and Asano Rivers running from south-east to north-west (Fig. 3). Alluvial lowland and terrace along these rivers are covered with built-up areas. The relative height of the terrace amounts to about 30 meters. This undulatory landform causes an irregular street pattern, which also characterizes the landscape of Kanazawa.

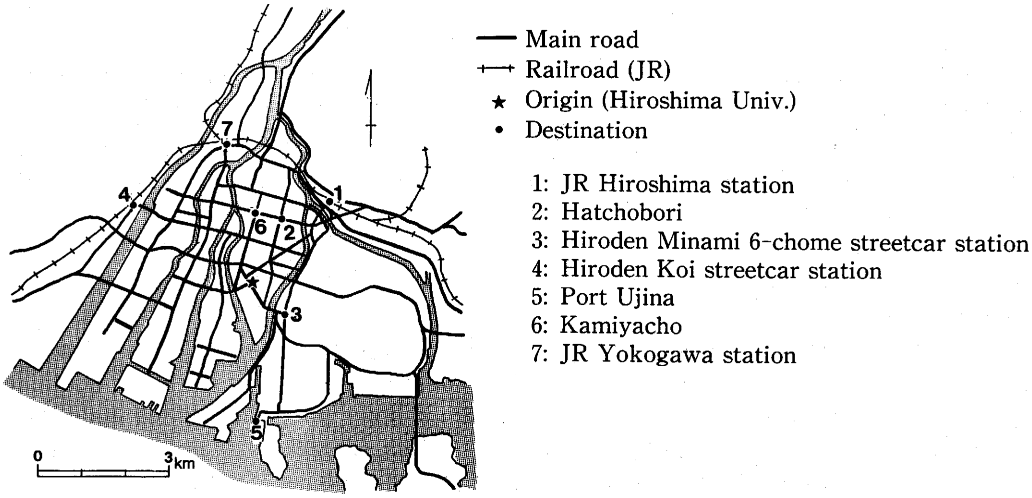


Fig. 2 Study area of the Hiroshima survey

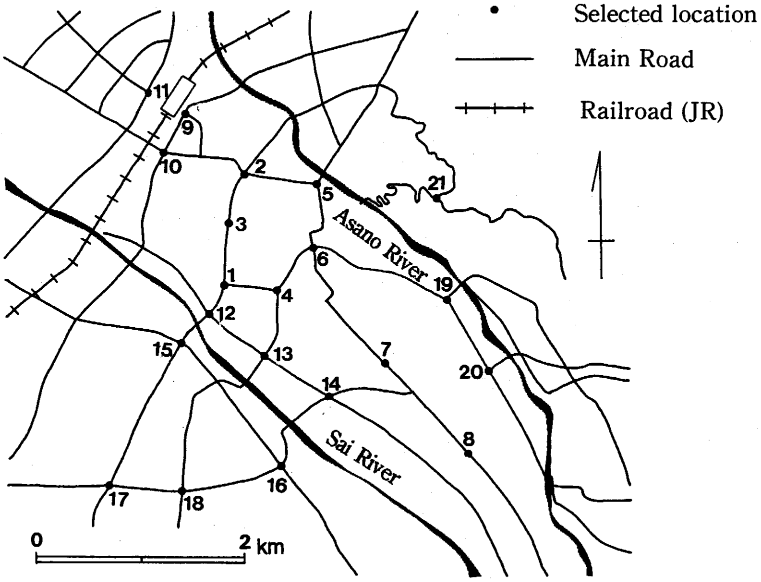


Fig. 3 Study area of the Kanazawa survey

1: Kohrinbo; 2: Musashi; 3: Minamicho; 4: Hirosaka; 5: Hashiba; 6: Kenrokuen-shita; 7: Ishibiki/University hospital; 8: Faculty of Technology, Kanazawa Univ.; 9: JR Kanazawa Station; 10: Rokumai; 11: Hirooka; 12: Katamachi; 13: Urokomachi; 14: Kasamai 3-chome; 15: Nomachi-Hirokohji; 16: Teramachi 1-chome; 17: Arimatsu; 18: Izumino; 19: Taimachi; 20: Asahimachi; 21: Bohkodai/Mt. Utatsu

In Tokyo, the urban form of the Yamanote Diluvial Upland is contrasted with that of the Shitamachi Alluvial Lowland. The study area lies in the south-western part on the Yamanote Line running around the eastern side of the Yamanote Diluvial Upland (Fig. 4). A lot of small dissected valleys as well as irregular street networks cover this area. The majority of movement within the city relies on public transportation, especially railroad and subway. As stated by Canter and Tagg (1975), Tokyo is such an intricate city that only railroad system can provide an overall structure for use as a reference in cognitive mapping.

The central part of Sapporo is covered with a grid-patterned street system planned and constructed after the Meiji era (Fig. 5). According to a rectangular coordinate system, a systematic address is assigned there in such a way that east-west and north-south axes are called *Chome* and *Jo* respectively. This pattern of urban area is rare in Japanese cities except Hokkaido. However, Sapporo will be a suitable study area for comparing the results of the analysis with those of the studies carried out in North American cities in which central parts are usually covered with such a systematic pattern of street and address.

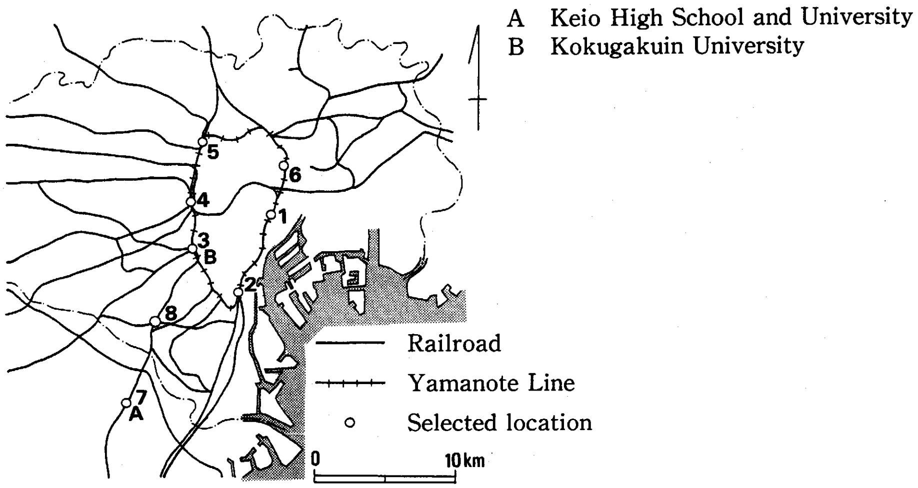


Fig. 4 Study area of the Tokyo survey

1: Tokyo; 2: Shinagawa; 3: Shibuya; 4: Shinjuku; 5: Ikebukuro; 6: Ueno; 7: Hiyoshi; 8: Jiyugaoka

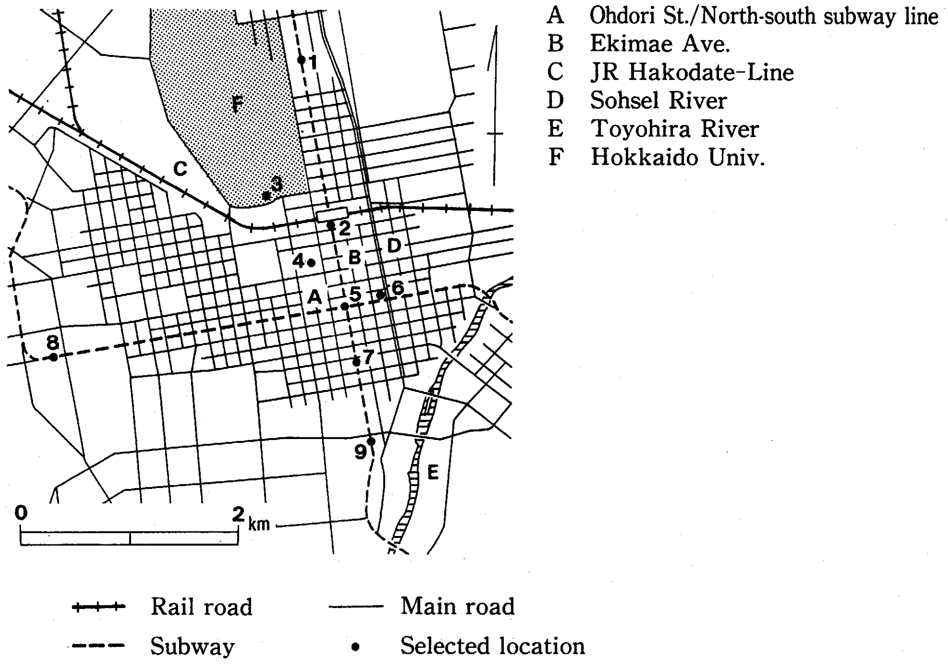


Fig. 5 Study area of the Sapporo survey

1: Kita 18-jo subway station; 2: JR Sapporo station (south gate); 3: Clark hall of Hokkaido Univ.; 4: Prefectural office; 5: Ohdori subway station; 6: Television tower; 7: Susukino subway station; 8: Maruyama Park subway station; 9: Nakajima Park subway station

Data

The data used in the present study were obtained by sketch mapping and distance estimation. As mentioned above, the sketch mapping entails such shortcomings as the inconsistency of results and the influence of the subject's drawing ability. To avoid these problems, the author employed the method of giving two reference points in advance and asking subjects to indicate only the remaining points on the questionnaire sheet. Students were chosen as subjects because their homogeneity in regard to intellectual level and developmental stage makes it easy to compare results among study areas under a consistent condition. The data were collected by the following questionnaire surveys:

The Hiroshima data were drawn from 122 students of Hiroshima University in July 1983 (Tanaka and Wakabayashi, 1985). Selected locations were seven transportation nodes within the central part of Hiroshima (Fig. 2). By way of a preliminary survey, these locations proved to be known by more than 90% of the students. The content of the questionnaire mainly consists of the direction and the distance estimations. Concerning the cognitive direction, subjects were requested to indicate the locations on the legal-size sheet where the reference point (*i.e.*, Hiroshima University), the north-south baseline, and the bar scale were given. Cognitive distance was measured in the manner of magnitude estimation asking subjects to estimate in 0.1 kilometers the crow-flight distance from the front gate of Hiroshima University to the remaining locations.

The Kanazawa data were obtained from 113 students of Kanazawa University in February 1992. The locations to be answered were 21 transportation nodes within the city (Fig. 3). By means of a preliminary survey, these proved to be known by more than 90% of the students. Among these locations, two major landmarks of CBD, Kohrinbo (Loc. 1; from now on, the location number will be abbreviated to "Loc.") and Musashi (Loc. 2), were selected as reference points. Then, subjects were asked to indicate the remaining locations on the legal-size sheet in which the two reference points were printed beforehand.

In the Tokyo survey, three samples of students differing in age and school were selected to examine whether the differences in their developmental stage and their zone of daily activities affect the spatial patterns of cognitive maps (Wakabayashi, 1989b; 1990a). The Tokyo-A data were drawn from 55 students of Keio High School in May 1987. The locations to be answered were six railroad stations on the Yamanote Line (Locs. 1-6) and Hiyoshi Station (Loc. 7) on the Toyoko Line (Fig. 4). These are assumed to be well-known to the subjects. The two reference points, Shibuya (Loc. 3) and Hiyoshi (Loc. 7), being prespecified, the subjects represented their cognitive maps by the following two methods: distance estimation which required subjects to indicate the crow-flight distance between the locations relative to the distance between the reference points printed in the questionnaire (see Appendix A); sketch mapping which asked subjects to indicate the locations excepting two reference points on the legal-size questionnaire (see Appendix B). In the same manner, the Tokyo-B data were collected in September 1988 from 53 students of Keio University adjoining Keio High School. In this survey, a letter-size questionnaire was used.

The Tokyo-C data were drawn from 50 students of Kokugakuin University in September 1988 and January 1989. This sample differs in location from the schools of

Tokyo-A and B. The locations to be answered were six railroad stations on the Yamanote Line (Locs. 1-6), used also in Tokyo-A and B surveys, and the Jiyugaoka Station (Loc. 8) on the Toyoko Line (Fig. 4). The two reference points, Shibuya (Loc. 3) and Jiyugaoka (Loc. 8), being prespecified, the subjects made sketch mapping and distance estimation in the same way as the Tokyo-A and B. In addition, they performed the rating scale estimation that requires to estimate the distances on a nine-point rating scale (see Appendix C).

The Sapporo data were drawn from the 170 students of Hokkaido University in October 1988 (Wakabayashi, 1990b). The locations to be answered were nine places within the central part of the city (Fig. 5). By way of a preliminary survey, these proved to be known by more than 90% of the students. Kita 18-jo Station (Loc. 1) and the south entrance to Sapporo Station (Loc. 2) were prespecified as reference points, the subjects performed sketch mapping and distance estimation in the same way as the Tokyo survey.

4. Absolute Distortions in Cognitive Maps

Most of the previous studies about cognitive direction and distance mainly dealt with the absolute distortion of cognitive maps. The following hypotheses were derived from these studies (Pocock, 1978; Tanaka and Wakabayashi, 1985):

(a) Intra-urban cognitive distance is generally greater than the objective distance; over-estimation declines with increasing physical distance.
(b) The general layout and topography of a city provide reference lines for conceptual structuring.
(c) Linearity of the route influences estimates for perceived journey.
(d) Distance judgements are influenced by the characteristics of the end points, which is recorded as non-commutative.

In addition, Pocock (1973) and Goodchild (1974) suggested the following hypotheses on the basis of the analyses of sketch maps:

(e) Intersections are seen as right angles.
(f) The cumulative effect of small curves is ignored.

According to Lloyd (1989), hypotheses of (a), (b) and (d) can be due to implicit scaling; those of (e) and (f) are regarded as results of alignment and rotation heuristics. In this chapter, these hypotheses about the absolute distortion are tested by using the data from Hiroshima and Kanazawa.

Cognitive map of Hiroshima

Table 2 summarizes statistics for the cognitive distance of the seven locations used in the Hiroshima survey. The absolute error indicates a tendency of over-estimation except for Loc. 3, supporting the hypothesis (a). Location 4 shows the largest relative error, which may be due to the four bridges or barriers lie along the route from the origin of Hiroshima University. This result is related to the hypothesis (c). Contrary to this hypothesis, distances to Locs. 2 and 6 to which no bridge lies along the route from the origin were also over-estimated. Considering the hypothesis (d), this tendency is account-

Table 2 Statistics of the cognitive distance for the sample of Hiroshima[1)]

Location	Mean	Standard deviation	Absolute error	Relative error (%)[2)]
1	27.9	13.4	2.9	11.6
2	18.6	11.3	2.6	16.2
3	10.3	4.5	−0.7	−6.1
4	43.6	22.3	12.6	40.8
5	32.9	12.6	0.9	2.8
6	18.7	11.4	2.7	17.0
7	38.0	23.9	5.0	15.3

1) The unit except that of the relative error is 100 meters.

2) Relative error $=\frac{\text{Mean of the cognitive distance}-\text{Actual distance}}{\text{Actual distance}}\times 100.$

ed for by the fact that it takes a relatively long time to go to these city-center places owing to traffic impediments and reduced speed.

Power functions of the following form were fitted to the relationship between the cognitive and the objective distances:

$$y = a\,x^{b}, \tag{5}$$

where y and x refer to cognitive and objective distances, and a and b are parameters to be estimated respectively. Table 3 shows parameter estimates obtained for individual subjects. Although the correlation coefficient varies between 0.434 and 0.999, the mean of them amounts to 0.882. This demonstrates that the power function fitted the data fairly well. According to the hypothesis (a), the b parameters have to be less than 1.0; but 70% of the samples were opposed to this and their mean value amounted to 1.16 (Table 3). Considering the fact that distance to the changeover point from over- to under-estimation increases with the size of city (Canter and Tagg, 1975; Pocock, 1978), the size of this study area may be too small to reach the changeover point. If the study area were large enough to reach this point, the distance-decay tendency suggested by the hypothesis (a) would appear.

Table 3 Regression results of cognitive vs. actual distances for the sample of Hiroshima

Parameter	Maximum	Minimum	Mean	Standard deviation
a	12.1	0.03	1.04	1.43
b	2.13	0.35	1.16	0.31
Correlation coefficient	0.999	0.434	0.882	0.111

Estimated directions were classified at intervals of 15 degrees for each point and illustrated in frequency polygons (Upton and Fingleton, 1989) as shown in Fig. 6. This figure indicates that the mode of the cognitive direction of each point deviates 5 or 20 degrees counterclockwise from the actual direction. This tendency also appeared in directional statistics shown in Table 4.

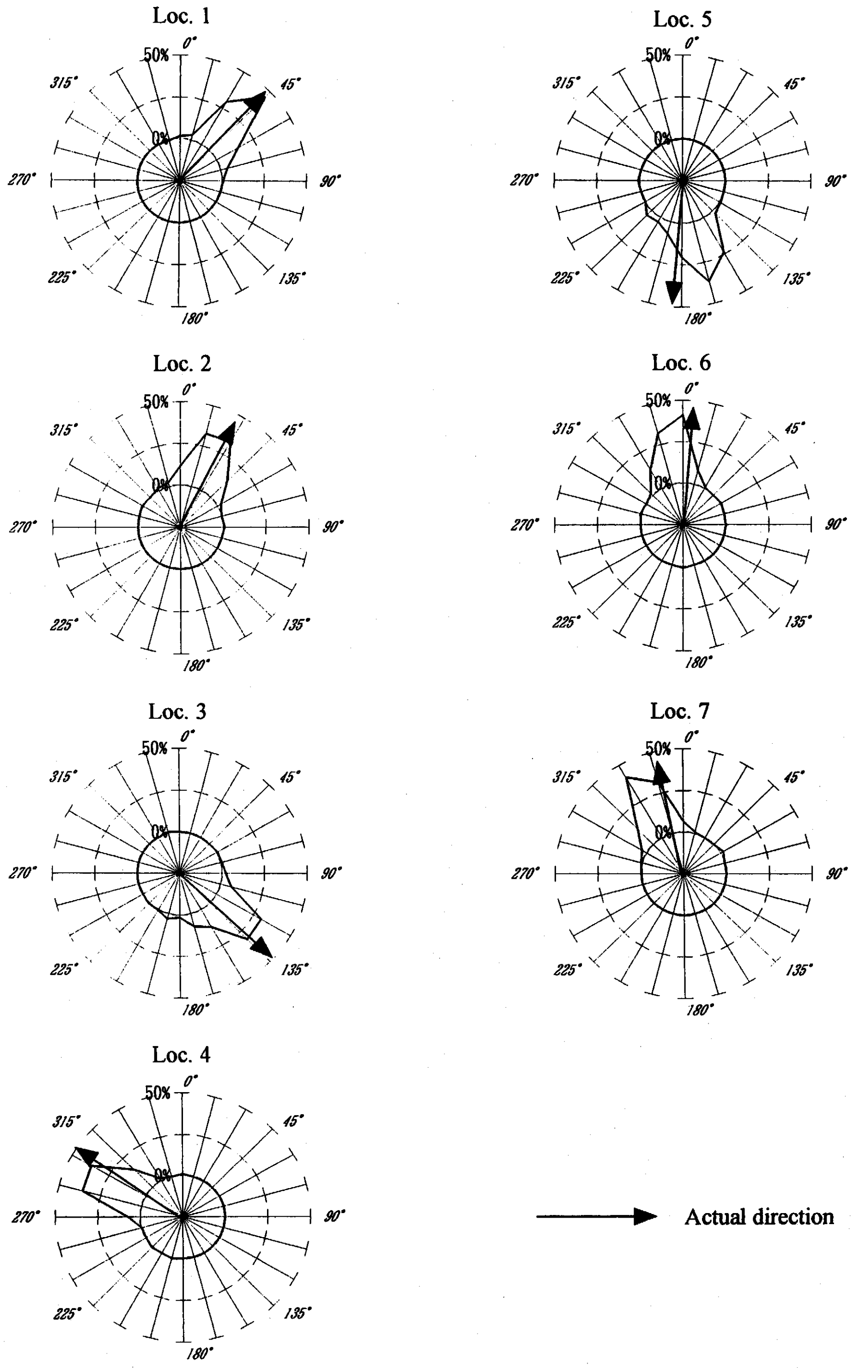


Fig. 6 Frequency distribution of cognitive directions in Hiroshima

Table 4 Statistics of the cognitive direction for the sample of Hiroshima

Location	Mean direction	Circular variance	Absolute error
1	36	0.03	6
2	16	0.05	8
3	127	0.10	9
4	287	0.04	17
5	162	0.07	16
6	345	0.05	19
7	328	0.04	22

All the units are degrees.

Comparing each of the points, the amount of deviation for locations (*e.g.*, Locs. 4 and 7) far from the origin is larger than that of locations (*e.g.*, Locs. 2 and 3) close to the origin. Thus, the cognitive direction varies with the distance from the reference point. These systematic distortions can be due to the fact that the river channels which seem to be reference lines for orientation in Hiroshima deviate from the cardinal direction. These results indirectly support the hypotheses (b) and (e).

Although one-dimensional properties of the cognitive map are clarified partly by analyzing cognitive distance and direction, it is evident that these analyses cannot capture the spatial properties of the cognitive map as a whole. Hence, in the next section, spatial patterns of absolute distortion are analyzed applying Euclidean regression to the Kanazawa data.

Cognitive map of Kanazawa

The coordinates of locations on the sketch maps of Kanazawa were transformed to fit the locations of two reference points (Locs. 1 and 2) into the actual ones. After cognitive maps for all samples were overlaid into the actual map in this manner, standard deviational ellipses were drawn for each of the 21 points to measure the distortion and fuzziness of the cognitive maps. The result is shown in Fig. 7, where the distortion is regarded as a composite of absolute and relative ones. This figure illustrates an increase in the amount of distortion and fuzziness with the distance from the reference points. It also indicates the outward shift of locations in cognitive maps from the actual ones, which implies that cognitive distance is over-estimated relative to the distance from the reference point. Specifically, locations in southern or eastern part of the city commonly indicate a counterclockwise shift, suggesting a directional bias in the cognitive map.

In order to separate the above described distortions into the absolute and the relative ones, Euclidean regression was performed for each of the cognitive configurations so as to fit it into the actual map. Table 5 summarizes parameter estimates of Euclidean regression. The value of parameter c referring to the scale change averaged 0.593. This value suggests that cognitive maps are enlarged to about twice the size of the actual map, which agrees with the hypothesis (a). Mean direction (Gaile and Burt, 1980) of the rotated angle indicated by θ amounts to -22.2 degrees, which suggests that cognitive maps are

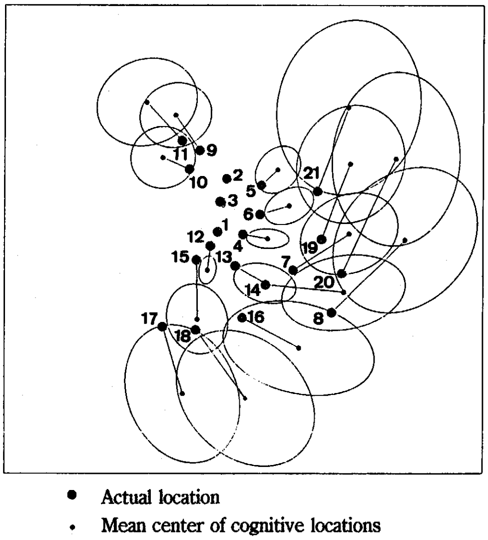


Fig. 7 Standard deviational ellipses with 1.0 standard deviations for locations in the cognitive map of Kanazawa (before Euclidean regression)

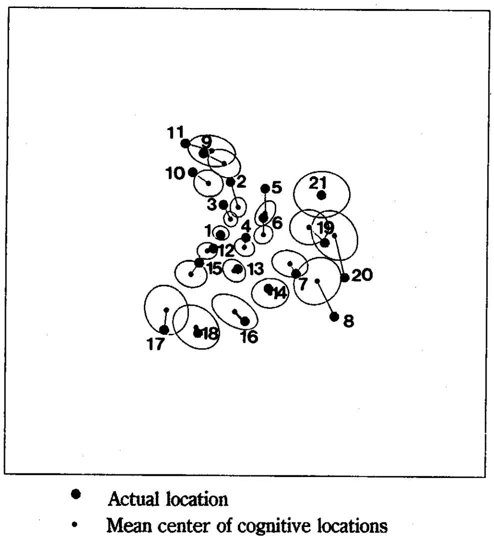


Fig. 8 Standard deviational ellipses with 1.0 standard deviations for locations in the cognitive map of Kanazawa (after Euclidean regression)

Table 5 Results of Euclidean regression for the cognitive map of Kanazawa

Parameter	Mean	Standard deviation
Scale (c)	0.593	0.17
Angle of rotation (θ deg.)	−22.2	14.0
Bidimensional correlation	0.911	0.061

Mean and standard deviation of the angle are directional statistics.

rotated counterclockwise about 20 degrees from the actual map. This tendency is due to the displacement of two river channels as major reference lines from cardinal directions. In other words, the river channels which are actually displaced about 35 degrees clockwise from the east-west line appear to be rotated counterclockwise to fit the cardinal directions in cognitive maps.

Euclidean regression overlaid the actual map with all the cognitive maps to eliminate absolute distortions. Figure 8 shows the overlaid map indicating relative distortion and fuzziness of cognitive maps by standard deviational ellipses. This map exhibits a smaller amount of distortion than Fig. 7, which implies that most of the distortions in Fig. 7 are attributed to the absolute one. Assuming that Fig. 7 shows the absolute distortion, the relationship between the relative and the absolute distortions can be captured by comparing the standard deviational ellipses in Fig. 8 with those in Fig. 7. Hence, the displacement of the mean center of ellipses from the actual location and the areas of the ellipses (Table 6) were measured for Figs. 7 and 8. The correlation coefficient for the area of

Table 6 Statistics of standard deviational ellipses for the cognitive locations in Kanazawa

Location	Area of ellipse		Displacement of mean center	
	a	b	a	b
1	—	0.06	—	0.03
2	—	0.08	—	0.48
3	0.01	0.05	0.07	0.29
4	0.20	0.09	0.44	0.18
5	0.52	0.11	0.40	0.44
6	0.43	0.09	0.54	0.30
7	1.93	0.23	1.18	0.21
8	5.06	0.55	1.83	0.70
9	1.15	0.22	0.77	0.40
10	0.98	0.19	0.51	0.34
11	2.16	0.35	0.93	0.48
12	0.12	0.08	0.44	0.12
13	0.61	0.13	0.61	0.07
14	2.28	0.27	1.38	0.09
15	1.06	0.21	1.07	0.25
16	3.43	0.35	1.14	0.25
17	3.84	0.52	1.25	0.36
18	4.46	0.48	1.51	0.11
19	3.14	0.33	1.44	0.40
20	5.48	0.55	2.27	0.77
21	6.23	0.64	1.60	0.01

a: Before Euclidean regression (Fig. 7), b: After Euclidean regression (Fig. 8).
All the units are relative ones, but a's correspond with b's units.

ellipse between the two maps was significant at 0.01 level ($r=0.981$); but that for the displacement of the mean center was not significant ($r=0.356$). This result suggests that the tendency of absolute distortion is rather different from that of the relative distortion, while there is a similarity in fuzziness between the absolute and the relative distortions. Therefore, it would be difficult to remove the effect of fuzziness by using Euclidean regression, even if absolute distortion is eliminated.

Assuming that the cognitive map has absolute origin, direction and scale identical with the actual map, there appeared such a remarkable absolute distortion as Fig. 7. However, supposing that the cognitive map has relative origin, direction and scale, the amount of distortion becomes smaller than that of absolute one as shown in Fig. 8. These results suggests the reason why people have no trouble with everyday life even if their cognitive maps entail a great deal of absolute distortion. In other words, they might adapt to their living environment by transforming absolute coordinates of cognitive maps into relative ones so as to reduce the amount of distortion. While the absolute distortion due to the Euclidean transformation is explained by general theories of cognition, the relative one is difficult to explain (Lloyd, 1989). Accordingly, the latent properties of cognitive maps will appear markedly in the relative distortion rather than the absolute one. Hence, the next chapter will deal with the hidden structure of cognitive maps in terms of their relative distortions.

5. Relative Distortions in Cognitive Maps

Assuming that the structure of the cognitive map differs from that of the actual map, sketch maps produced on the supposition that the cognitive map entails Euclidean properties identical with the cartographic map might give some bias to internal representations. Indirect mapping is evidently more suitable for drawing internal representations with little restriction than direct mapping.

Analysis of the data collected through indirect mapping necessitates some procedure for representing the cognitive map into such a form as is comparable with the actual map. Concerning this problem, a procedure has been developed for recovering cognitive configurations from the data of cognitive distances by employing MDS. Specifically, this procedure can reduce the constraints on data collection because nonmetric MDS permits us to use ordinal data as well as metric ones. In addition, the "stress" value of MDS that indicates badness-of-fit between input data and recovered configuration enable us quantitatively to examine the geometric properties of cognitive maps.

This section deals with the relative distortion of cognitive maps employing nonmetric MDS. In this analysis, the data from sketch mapping were also used to examine the reliability and validity of the method.

Cognitive map of the Yamanote Line

Recovery of cognitive maps by MDS

Before recovery of cognitive maps by means of MDS from the estimated distances in Tokyo, it is necessary to examine metricity of the data. In geometric terms, for certain elements x and y in the set of points, if the relation $d(x, y)$ indicates metric distance, it must bear the following axioms of distance:

$$d(x, x) = 0 \text{ and } d(x, y) = 0, \text{ if } x=y \tag{6}$$

$$d(x, y) = d(y, x) \tag{7}$$

$$d(x, y) + d(y, z) \geqq d(x, z). \tag{8}$$

It is evident that sketch maps possess all these properties because they were drawn on two-dimensional plane. On the other hand, estimated distance was measured on the supposition that it bears identity (Eq. (6)) and symmetry (Eq. (7)), but whether it satisfies triangle inequality (Eq. (8)) is not yet known. Hence, this property was empirically examined for the distance estimates derived from the Tokyo survey, with the result that the number of samples satisfying triangle inequality was only seven in 55 for Tokyo-A, three in 53 for Tokyo-B, and two in 50 for Tokyo-C respectively. This result indicates a nonmetric nature of the cognitive map, although measurement error and the difference in dimensions of estimation probably affected it. In any case, it necessitates the application of nonmetric MDS to recover cognitive configurations from these data.

Two-dimensional configuration was obtained for each datum of distance estimates using nonmetric MDS algorithm, KYST2A. As an index of how well the recovered configuration matches the input data, stress value was calculated. This index is defined as

$$S = \sqrt{\frac{\sum_{i<j}(d_{ij}-\hat{d}_{ij})^2}{\sum_{i<j} d_{ij}^2}} \tag{9}$$

where d_{ij} denotes the distance between i and j, and $\hat{d}_{ij}$ is a value which is monotonic with the dissimilarity between i and j of the input data. The value of S varies from 0.0 to 1.0 with 0.0 indicating perfect fit. As shown in Table 7, stress values for Tokyo-B are lower than those for Tokyo-A, implying that the cognitive maps of university students have a better fit to the Euclidean space than those of high school students. Concerning the result for Tokyo-C, stress values for the method of rating scale are lower than those of distance estimation. This indicates that the method of rating scale produces a better fit of configuration to Euclidean space than distance estimation.

Yet, we can say that MDS recovers a two-dimensional cognitive map comparable with the actual one because all the mean values of stress are less than 10% which refers to a "fair fit" (Hayashi and Akuto, 1976, p. 81).

Table 7 Frequency distribution of stress values for the sample of Tokyo

Stress	Sample group			
	Tokyo-A	Tokyo-B	Tokyo-C	
	a	a	a	b
.000－.020	35	41	17	40
.021－.040	5	8	11	3
.041－.060	5	3	7	5
.061－.080	2	0	11	1
.081－.100	6	0	3	1
.101－	2	1	1	0
Mean	.032	.017	.039	.016
Standard deviation	.034	.020	.029	.018

a: Distance estimation, b: Rating scale methed.

Overall properties of distortions

Each cognitive map was fitted to the actual one by Schönemann and Carroll's (1970) procedure of Procrustes rotation, then bidimensional correlation was calculated to measure the correspondence between the cognitive and the actual maps. Table 8 indicates that the mean value of bidimensional correlation for sketch maps is greater than that for distance estimates. A significant difference in bidimensional correlation between these two methods is detected for all samples at the 0.01 level in accordance with Wilcoxon matched-pair signed ranks test (Table 9). As regards the method of rating scale for Tokyo-C, bidimensional correlations are also significantly lower than those of

Table 8 Frequency distribution of bidimensional correlation between the cognitive map of Tokyo and the actual map

Bidimensional correlation	Sample group						
	Tokyo-A		Tokyo-B		Tokyo-C		
	a	b	a	b	a	b	c
.00− .20	0	0	0	0	0	0	0
.21− .40	0	0	1	0	0	0	0
.41− .60	1	0	1	0	2	0	1
.61− .80	16	6	6	1	6	1	3
.81−1.00	38	49	45	52	42	49	46
Mean	.848	.893	.875	.923	.880	.942	.897
Standard deviation	.111	.071	.022	.047	.109	.049	.099

a: Distance estimation, b: Sketch mapping, c: Rating scale methed

Table 9 Wilcoxon matched-pairs signed ranks tests for the difference in bidimensional correlation between methods of extracting cognitive maps

Test case	Standardized test statistic		
	Tokyo-A	Tokyo-B	Tokyo-C
Distance estimation vs. Sketch mapping	−2.384*	−2.930*	−3.446*
Rating scale method vs. Sketch mapping	—	—	−3.417*
Rating scale method vs. Distance estimation	—	—	1.680NS

*: Significant at 0.01 level, NS: Not significant at 0.05 level.

sketch maps; but it has no significant difference with the result of distance estimation.

MacKay (1976) and Buttenfield (1986) obtained similar results, which can be attributed to the difference in the nature of the task required of the subjects between sketch mapping and distance estimation. Specifically, sketch mapping tends to produce more consistent result than distance estimation because sketch mapping enables subjects to observe the map during the task, while distance estimation requires subjects to make somewhat abstract inference.

Concerning the difference between samples, mean values of bidimensional correlation for Tokyo-B and C are greater than for Tokyo-A (Table 8). This implies that the cognitive maps of university students are more similar to the actual map than those of high school students. In other words, supposing that the age of the subject corresponds with the developmental stage, similarity between the cognitive and the actual maps increases with progress in the developmental stage. However, aforementioned results are not directly associated with the developmental stage because all the subjects of the present study are assumed to have reached the formal operational stage. According to the Piaget's developmental theory (Hart and Moore, 1973), people have an ability to use Euclidean reference system at this stage. Hence, there is no difference between the high school and the university students in the developmental stage of the ability to use the spatial reference system.

In considering the developmental stage, environmental cognition ought to be distinguished from fundamental spatial relations (Liben, 1981, p. 15). The former refers to an individual's knowledge about specific spaces, while the latter is concerned with his notion about space. According to this distinction, the difference in stress values between the high school and the university students (Table 7) is associated with fundamental spatial relations, while the difference in bidimensional correlation (Table 8) seems to be related to environmental cognition.

Local properties of distortions

The cognitive maps overlaid into the actual map were aggregated by standard deviational ellipses. The results are shown in Table 10 and Fig. 9.

For all samples, the displacement of the mean centers of ellipses from the actual location indicates a common tendency. Specifically, the Yamanote Line that is actually like in an ellipse-like form is transformed into a configuration approximating a circle. In addition, pairs of stations (such as Locs. 5 and 6, Locs. 1 and 4, Locs. 2 and 3) locating the eastern and western side of the Yamanote Line are displaced into symmetrical positions. This tendency to simplify the configuration also appeared in the study of Canter and Tagg (1975) carried out in Tokyo. On the other hand, Locs. 7 and 8 shift toward the Yamanote Line. This shift is attributed to the fact that it takes a relatively shorter time to travel from these stations to the Yamanote Line because express stops

Table 10 Statistics of standard deviational ellipses for the cognitive map of Tokyo

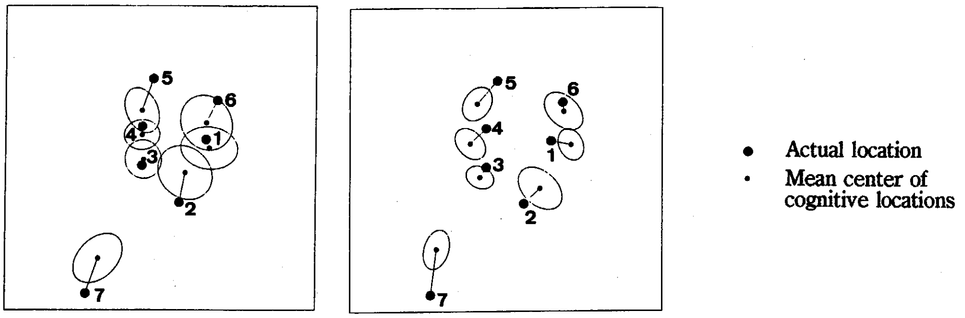
1) Area of ellipse (km^2)

Location	Tokyo-A		Tokyo-B		Tokyo-C		
	a	b	a	b	a	b	c
1	15.9	5.0	9.0	3.9	6.6	2.0	5.5
2	19.1	10.9	11.3	6.0	6.4	5.3	6.4
3	9.1	4.0	5.0	3.6	2.5	1.0	4.6
4	8.9	5.8	6.9	3.9	5.4	2.0	3.5
5	9.7	6.3	8.6	6.5	4.1	3.2	5.0
6	18.6	8.5	12.9	4.2	5.0	2.1	5.5
7	14.5	6.5	14.2	6.8	—	—	—
8	—	—	—	—	10.1	4.0	9.5

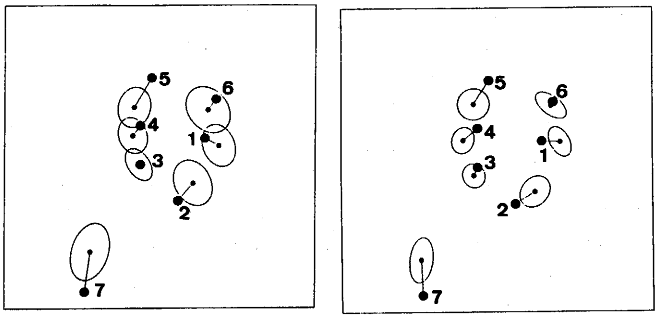
2) Displacement of mean center (km)

Location	Tokyo-A		Tokyo-B		Tokyo-C		
	a	b	a	b	a	b	c
1	0.85	1.77	1.45	1.61	0.99	1.00	0.91
2	2.78	2.02	2.12	2.10	1.85	1.63	1.73
3	0.57	1.08	0.12	0.82	0.15	0.15	0.70
4	0.78	2.01	1.15	1.72	0.89	0.92	0.75
5	3.10	2.79	3.14	2.59	2.10	1.34	1.91
6	2.28	0.87	1.23	0.37	1.47	1.16	1.25
7	3.42	4.26	3.74	3.27	—	—	—
8	—	—	—	—	2.92	1.70	2.16

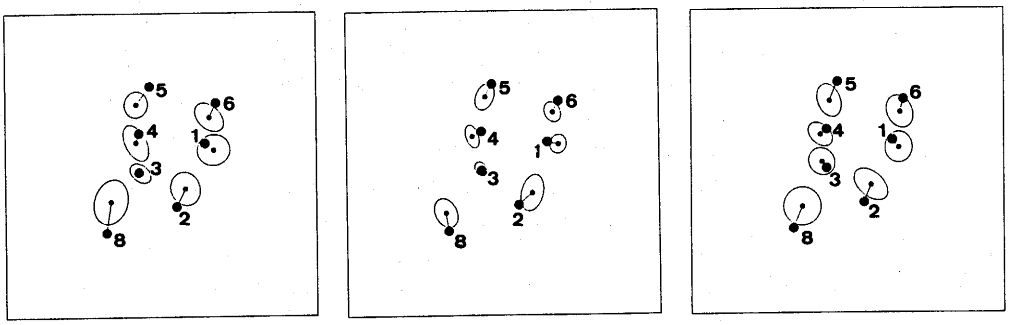
a: Distance estimation, b: Sketch mapping, c: Rating scale method.



a) Tokyo–A: distance estimation b) Tokyo–A: sketch mapping



c) Tokyo–B: distance estimation d) Tokyo–B: sketch mapping



e) Tokyo–C: distance estimation f) Tokyo–C: sketch mapping g) Tokyo–C: rating scale method

Fig. 9 Standard deviational ellipses with 1.0 standard deviations for locations in the cognitive map of Tokyo

there. The amount of displacement appears remarkable for the stations out of the Yamanote Line (Locs. 7 and 8) and its northern and southern sides (Locs. 2 and 5), although there appears little difference between the samples (Table 10).

Sizes of ellipses referring to fuzziness are somewhat different among samples. For Tokyo-A, ellipses of the eastern part of the Yamanote Line are greater than those of the western part. Nevertheless, all samples show a common tendency that sizes of ellipses for the locations out of the Yamanote Line (Locs. 7 and 8) are greater than the remaining ones. The overlapped area between ellipses indicating a degree of locational confusion appears remarkable among the stations in the eastern or southern part of the Yamanote Line (*e.g.*, Locs. 1, 2 and 6 or Locs. 3, 4 and 5). The sizes of ellipses for Tokyo-B are smaller than those for Tokyo-A, implying that individual difference in cognitive map of the university students is smaller than that of the high school students.

The difference in the size of the ellipse among locations might be due to Euclidean transformation based on the ordinary least squares (OLS) employed in fitting the cognitive map to the actual map. Thus, the tendency that the sizes of ellipses increase with the distance from the center of the configuration, as appeared in Fig. 9, can be attributed to the method that performs rotation around the mean center of the map (Wakabayashi, 1989b). Nevertheless, as described in the previous section, the results for the Kanazawa data indicated that Euclidean regression makes little change in the relative sizes of the ellipses. On the basis of these facts, it can be said that the fuzziness for the peripheral locations is greater than that for the central ones.

Validity and reliability of the method

The aforementioned results indicated to some extent a similar tendency among samples, proving the employed methods to be reliable. The analyses described above are based on an assumption that there is a single internal representation of the cognitive map and its property appears in the common tendencies among external representations extracted by different methods. However, there appears some difference in the distortions between methods.

For instance, sketch maps tend to approximate the configuration of the Yamanote Line to a circle, while distance estimates indicate a tendency that groups of stations located in either the western or eastern part of the Yamanote Line become close together (Fig. 9). Richardson (1981b, pp. 329-330) also reported such a contrast between methods. Thus, the configuration of the sketch map tends to be well-balanced, while that of distance estimation is likely to form clusters of close locations.

Explanation for these differences will vary with the conceptual framework of research. Assuming a single internal representation of the cognitive map, the validity of the method by which they are extracted becomes a significant issue. In order to examine it, MacKay (1976) and Baird *et al.* (1979) conducted a test asking subjects to evaluate

Table 11 Result of the self-evaluation test for the cognitive map of Tokyo

Judged similarity to the actual map	Frequency a	b	c
First	4	34	12
Second	19	12	19
Third	27	4	19
Total	50	50	50

a: Distance estimation.
b: Sketch mapping.
c: Rating scale method.

their own cognitive maps themselves. A similar test was performed for the subjects of the Tokyo-C survey. The procedure of this test was first to present three cognitive maps obtained by different methods, and then to require subjects to rank them with respect to how similar they were to their image of the actual map. Table 11 shows that the majority of the subjects feels sketch maps mostly resemble the actual map. A similar fact was reported by MacKay (1976).

Nevertheless, this test only deals with criterion-related validity. Validity ought to be examined also with respect to construct validity (Ohyama *et al.*, 1971). In this respect, subjects' self-evaluation cannot become the criterion of validity unless the cognitive map is supposed to have two-dimensional Euclidean properties. Since the so-called "imagery debate" (Lloyd, 1982), however, recent studies in cognitive psychology negated the assumption that the internal representation of the cognitive map has the same form as the actual map. Therefore, we should rather think that each method extracts different aspects of cognitive maps. From this point of view, we cannot conclude from the test of the subjects' self-evaluation that sketch mapping is the most valid among three methods.

Cognitive map of Sapporo

Overall properties of distortions

The previous analysis employed a method to fit the cognitive map into the actual one by means of Euclidean transformation because this makes it easy visually to compare cognitive maps with the actual map. Considering that the left and the right sides of the equation of Euclidean regression (Eq. (1)) refer to the dependent and the independent variables respectively, cognitive maps ought to be the dependent variable. In contrast with the previous analysis, therefore, the present section conducts Euclidean regression letting (u_i, v_i) and (x_i, y_i) in Eq. (1) be coordinates of the cognitive and the actual maps

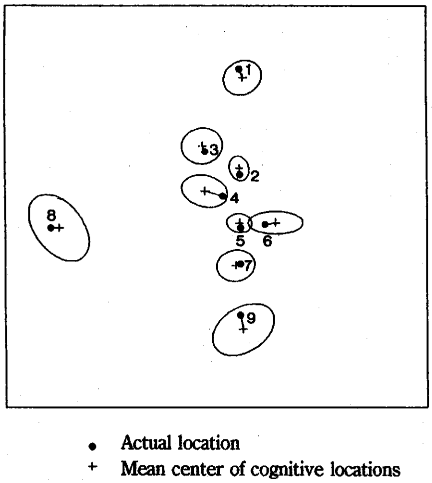


Fig. 10 Standard deviational ellipses with 1.0 standard deviations for locations in the cognitive map of Sapporo derived from sketch mapping

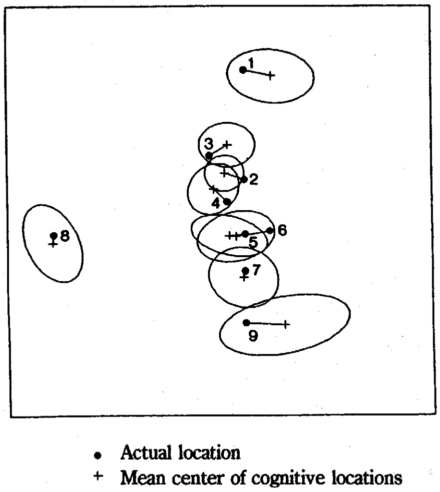


Fig. 11 Standard deviational ellipses with 1.0 standard deviations for locations in the cognitive map of Sapporo derived from distance estimation

respectively. In addition, inverse transformation was performed for the transformed configuration to aggregate cognitive maps by standard deviational ellipses (Wakabayashi, 1990b, p. 270). Results of the analysis are depicted in Figs. 10 and 11.

Bidimensional correlations between the actual and the cognitive maps averaged 0.953 for sketch mapping and 0.882 for distance estimation (Table 12). This indicates that sketch mapping is likely to produce more similar configuration with the actual map than distance estimation, coinciding with the result reported in the preceding section. In addition, a minute comparison of Tables 8 and 12 shows that correspondence of the cognitive map of Sapporo with the actual map is better than that of Tokyo.

Table 12 Frequency distribution of bidimensional correlation between the cognitive map of Sapporo and the actual map

Bidimensional correlation	Distance estimation a	Distance estimation b	Sketch mapping a	Sketch mapping b
— .40	0	0	0	0
.41— .50	1	1	0	0
.51— .60	0	1	0	0
.61— .70	5	3	1	0
.71— .80	16	14	7	12
.81— .90	58	56	11	37
.91—1.00	90	95	151	121

a : Correlation with the cartographic map.
b : Correlation with the route-distance space.

Even if the configuration of cartographic map becomes an independent variable, it can be regarded as merely one of the standards to measure the distortion in cognitive maps (Downs, 1981a). Although the rectangular grid of the street system is a distinctive feature of the physical environment in Sapporo, the cartographic configuration cannot fully reflect this property. Euclidean metric of the cartographic map ought to be replaced by a city-block metric in order to incorporate this feature into the analysis because the distance of the shortest route between the two points on the rectangular grid corresponds to the city-block distance. Hence, the two-dimensional configuration called "route-distance space" was recovered from the route-distance matrix by MDS, being incorporated into the Euclidean regression as an independent variable. The recovered configuration is simply an approximate one because such a route-distance space in Sapporo has non-Euclidean properties. Nevertheless, the stress value for this configuration was less than 0.01, indicating an "excellent fit" for the input data.

Figure 12 was obtained by fitting the recovered route-distance space into the actual map by means of Euclidean regression. In the rectangular street pattern of Sapporo, route-distance between diagonal locations tend to be longer than the distance between locations along a line parallel with the street. This tendency is reflected in the bending line of locations along the major street of the north-south axis as illustrated in Fig. 12.

Table 12 summarizes bidimensional correlation of the route-distance space with the cognitive map. For distance estimation, the correlation of the cognitive map with the

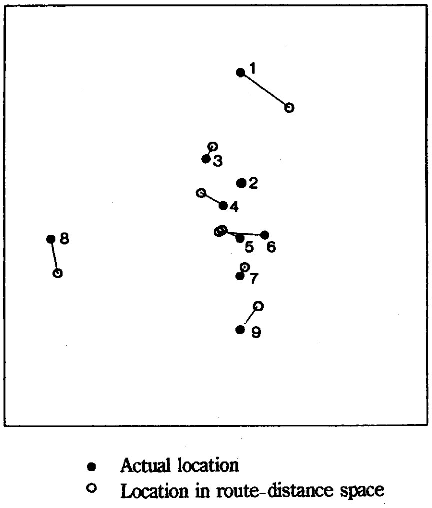


Fig. 12 Configuration of points in route-distance space best fitted to the actual map

route-distance space is higher than with the cartographic map. The difference between them is significant at the 0.05 level, in accordance with the Wilcoxon matched-pairs signed ranks test (Table 13). For sketch mapping, the correlation of the cognitive map with the cartographic one is higher than with the route-distance space, being significant at the 0.001 level.

Table 13 Wilcoxon matched-pairs signed ranks tests for the difference between "actual maps" in bidimensional correlation

Method	Mean of bidimensional correlation a	Mean of bidimensional correlation b	Standardized test statistic	Probability of occurance
Distance estimation	.8824	.8913	−2.107	<.05
Sketch mapping	.9526	.9095	10.190	<.001

a: Cartographic map, b: Route-distance space.

Local properties of distortions

Table 14 shows statistics of standard deviational ellipses in Figs. 10 and 11. According to these table and figures, sketch mapping indicates that the locations on the subway line shift along its route in common, while the amount of displacement between the cognitive and the actual maps is larger than that of distance estimation. This tendency suggests that distortions in cognitive maps are partly determined by the transportation axis that is regarded as a reference line for locational cognition.

On the other hand, distance estimation reveals a tendency similar to that of route-distance space. Specifically, Locs. 1 and 9 being the north-eastern or south-eastern side of Loc. 8 shift away from Loc. 8, while Locs. 5 and 6 being the eastern side of Loc. 8 shift toward Loc. 8 (Fig. 11). As a result, the array of locations on the north-south axis forms a curve in the same manner as in Fig. 12.

Table 14 Statistics of standard deviational ellipses for the cognitive locations in Sapporo

Location	Displacement of mean center (km)		Area of ellipses (km²)	
	a	b	a	b
1	0.401	0.139	0.770	0.222
2	0.298	0.095	0.228	0.081
3	0.303	0.094	0.403	0.250
4	0.266	0.263	0.417	0.248
5	0.223	0.074	0.491	0.079
6	0.484	0.159	0.636	0.209
7	0.097	0.070	0.693	0.205
8	0.122	0.120	0.708	0.617
9	0.553	0.212	1.246	0.503

a: Distance estimation, b: Sketch mapping

The size of the ellipse referring to fuzziness is greater for distance estimation than for sketch mapping. This implies that the cognitive map derived from sketch mapping tends to contain a smaller fuzziness than that derived from distance estimation. A comparison between points reveals that the sizes of ellipses for peripheral locations are greater than those for central ones. These tendencies coincide with the results for Tokyo and some other studies (*e.g.*, Gale, 1982; Lloyd, 1989).

Non-Euclidean properties of cognitive maps

As inferred from the above results, the cognitive map of Sapporo is influenced by the route-distance in the rectangular grid pattern of streets, which is better represented in a space of city-block metric than in Euclidean space. Accordingly, the author examined which distance metric is best fitted for the distance estimates by comparing stress values for configurations recovered from the data in various Minkowskian metrics, in the same way as Richardson (1981a). Minkowskian metrics are defined as

$$d(x, y) = (\sum_{i=1}^{R} | x_i - y_i |^{P})^{1/P}, \tag{10}$$

where $d(x, y)$ refers to distance from x to y, R is the number of dimensions, and P is the Minkowskian metric parameter. The city-block, Euclidean, and dominance metrics are defined respectively, by $P=1$, $P=2$, and $P=\infty$ (Gatrell, 1983, p. 28).

Table 15 summarizes stress values for each metric. This table shows that stress values for the configuration of the city-block metric are lower than those for the other metrics. Conducting the Wilcoxon matched-pairs signed ranks test, this tendency was

Table 15 Mean and standard deviation of stress values in each metric

Metric	Mean	Standard deviation
City-block	.034	.025
Euclidean	.044	.025
Dominance	.046	.028

Table 16 Wilcoxon matched-pairs signed ranks test for the difference in stress values between metrics

Test case	Standardized test statistics	Probability of occurrence
City-block vs. Euclidean	−5.013	<.001
City-block vs. Dominance	−5.443	<.001
Euclidean vs. Dominance	−1.923	<.001

statistically significant at the 0.001 level (Table 16). In addition, out of 170 subjects, 59% of them have the lowest stress values for the city-block metric. This percentage is remarkably greater than that of Richardson (1981a, p. 476) whose result indicated only 5.8%. The difference in this percentage may be due to the size of study area. Specifically, his study area of metropolitan Columbus containing the suburbs is larger than that of the present study. If the study was conducted across a broader area of Sapporo, the aforementioned percentage would fall owing to the influence of the other elements of the physical environment such as the river channels or railroads.

In this section, the spatial structure of cognitive maps was examined by conducting a quantitative analysis of relative distortions in cognitive maps of Tokyo and Sapporo. While the cognitive map of Tokyo showed a transformation of the Yamanote Line to a well-balanced form, that of Sapporo entailed a distortion partly determined by the grid pattern of the street system. These tendencies commonly appeared in the results for sketch mapping and distance estimation, which goes to support the reliability of the methods.

A minute comparison, however, indicates some distinctive tendencies for each method: sketch mapping leads to a smaller distortion and fuzziness than distance estimation. Specifically, the configuration obtained by distance estimation in Sapporo better fits with the route-distance space rather than the cartographic map. This implies that the internal representation contains the properties of route map as well as those of survey map. Accordingly, the cognitive map recovered from distance estimates appears to have an essentially non-Euclidean nature.

If different methods for extracting cognitive maps produce different results, their validity has to be examined. The subjects' self-evaluation of their cognitive maps indicated that sketch mapping is superior in criterion-related validity (Table 11). Validity ought to be examined also in regard to construct validity. As mentioned above, recent studies in cognitive science negated the assumption that internal representation had the same form as the actual map. In the next chapter, an explanatory framework for cognitive mapping is presented on the basis of the models of cognitive science in order to discuss the factors affecting the spatial patterns in cognitive maps.

6. Discussion: Factors Affecting the Spatial Patterns in Cognitive Maps

Results of the analysis described in the preceding chapter showed that different methods of extracting cognitive maps produce different representations. This implies that people possess some different types of cognitive maps in the head. Related to this issue, recent works in cognitive psychology concluded that imagery is reconstructed in a quasi-pictorial form on the basis of information obtained from long-term memory and stored in a propositional form (Kosslyn, 1981). Therefore, the aforementioned results can be due to the difference in the manner of information-processing by which cognitive maps are represented. In this chapter, the relationship between the process of cognitive mapping and the spatial pattern of cognitive map is discussed in accordance with the information-processing model of cognitive science.

The factors causing distortions

On the basis of the information-processing model, the process of cognitive mapping is divided into i) acquisition of environmental information, ii) encoding, iii) memory storage, iv) decoding, v) reproduction/usage, and vi) transformation, as shown in Fig. 13 (Downs and Stea, 1973; Lloyd, 1989; Wakabayashi, 1990b). According to these stages, the author will summarize the relevant findings as a preliminary to a discussion of the factors affecting the distortions in cognitive maps.

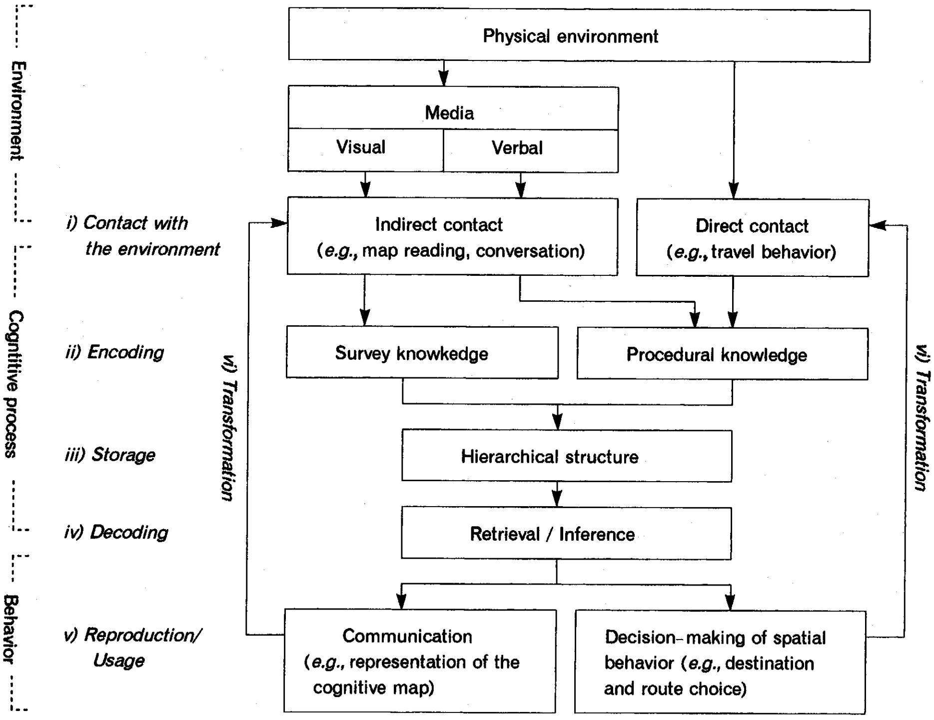


Fig. 13 Conceptual scheme for cognitive mapping process based on the information-processing model

i) Acquisition of environmental information

This stage is divided into the direct contact with the physical environment and the indirect one. As for the direct contact, spatial representation is formed by the perception of landmarks or by the kinesthesis during behavior in space. A considerable part of the previous studies of cognitive maps regarded the direct contact as a primary factor of cognitive mapping. For example, numerous studies conducted such an experiment as Tolman (1948), examining the route learning of an unfamiliar environment not only for animals but also for mankind.

By contrast, indirect contact refers to acquisition of environmental information through media (*e.g.*, maps, TV, radio, printings) and conversations. In this process, communication is performed through symbolic signs that induce meanings rather than mere signals accompanied by conditional reflex. Hence, the indirect contact can be regarded as an information source peculiar to human beings. Related to the cognitive mapping through media, cartographers have recently conducted some studies of the process of cartographic communications, especially regarding the perception and design of maps (Lloyd and Steinke, 1976, 1977 and 1984; Steinke and Lloyd, 1983). Although their relationship with cognitive mapping has just begun to be treated by Lloyd (1989) and MacEachren (1992), the number of studies concerning the effect of indirect contact was fewer than that of direct contact. In order to approach environmental cognition in the present condition of society characterized by the increasing importance of mass communication, we ought to call more attention to the process of indirect contact through media (Burgess and Gold, 1985).

Relating these information sources to the findings obtained in the present study, the fact that the cognitive map of distance estimation in Sapporo resembled the configuration of the route-distance space is attributed to the direct contact with the environment through travel. By contrast, the tendency to transform the Yamanote Line into an approximate circle can be influenced by cartographic media such as the route map of the railroad that usually has distortions like the cognitive map.

The difference in spatial patterns of distortions between the study areas is also caused in this stage. These patterns were mainly affected by the reference lines of the physical environment, namely the river channels in Hiroshima and Kanazawa, the railroad in Tokyo and the street system in Sapporo. Obviously, the reference line reflects the feature of each physical environment; the mode of contact with the environment determines which element becomes the reference line.

ii) Encoding

Environmental information entering into the short-term memory is encoded by activating related information in the long-term memory. This stage performs not only data-driven (bottom-up) processing, such as feature selection or chunk detection, but also conceptually driven (top-down) processing designed to match the framework of knowledge (schema or frame).

The spatial information to be encoded is divided into procedural knowledge about how to travel between places and survey knowledge about the global spatial relations among places. People acquire procedural knowledge from direct contact with an environment, while they acquire survey knowledge from indirect contact through cartographic media (Thorndyke and Hayes-Roth, 1982). The cognitive maps learned by direct contact are likely to exhibit a greater difference among individuals than those learned by indirect contact (Evans and Pezdek, 1980). Specifically, the cognitive maps acquired through cartographic media tend to have systematic distortions owing to the perceptual organization such as rotation and alignment heuristics (Tversky, 1981). A considerable part of the absolute distortions which appeared in the cognitive maps of Hiroshima and Kanazawa are attributable to these encoding processes.

iii) Storage

The encoded information is transferred to long-term memory and their interpreted meaning is stored in a propositional form. Stevens and Coupe (1978) suggested that landmarks were stored in a hierarchical structure according to their functional characteristics. This hierarchical network of propositions seems to be common to knowledge in general (Murakoshi, 1987). If the spatial knowledge is hierarchically organized in long-term memory, distortions of lower order landmarks in the cognitive map would be determined by those of higher order ones (Couclelis *et al.*, 1987). If such a hierarchical structure of cognitive maps can be grasped, the relationship between overall and local properties of distortions will be better explained.

iv) Decoding

As the need arises, the information stored in long-term memory is retrieved, decoded, and transferred to short-term memory. This process corresponds to remembering, in which a part of long-term memory is not directly reproduced but reconstructed by utilizing both the external cue and the stored information (Tulving, 1983). Therefore, the task required of subjects in the present study is regarded as a constructive process with remembering. As a result, different manners of this task are likely to produce different cognitive maps.

Concerning the relationship between the decoding process and the distortion in cognitive maps, it has been pointed out that the distances between places closer to a reference point are expanded relative to distances between places farther away. Holyoak and Mah (1982) explained this tendency by implicit scaling which causes asymmetrical cognitive distance. In addition, rotation and alignment heuristics can affect this decoding process producing a well-balanced cognitive map.

The decoded information is transferred to short-term memory entering consciousness, but whether its form become pictorial or propositional is determined by the manner of decoding and retrieval. Although the present study dealt only with pictorial decoding and assumed a symmetrical cognitive distance, an alternative methodology would clarify the other aspects of cognitive maps.

v) Reproduction and usage

An important issue of cognitive mapping concerns its function and usage. The usage of the cognitive map is divided into the execution of spatial behavior and communication. Most of the previous studies focused their attention upon the latter aspect by analyzing the properties of external representations. However, the research on cognitive maps was originally begun in order to explore the former aspect, in which cognitive maps cannot always be externally represented.

The process of spatial behavior consists of several different stages. Gärling *et al.*

(1984) divided this process into action plan, travel plan, and execution of travel plan. Of these stages, the cognitive map is concerned mainly with the last two. These two stages can also be called destination/route choice and navigation respectively. Most of the psychologists and planners directed their interest to the relationship which the cognitive map bore to navigation. However, little is known about the relationship between the cognitive map and destination/route choice with which geographers have been concerned. In order to clarify this, the methodology has to be improved in ecological validities by fitting it to the behavioral context.

vi) Transformation

The execution of spatial behavior causes direct contact with the environment and an acquisition of renewed information, bringing about further changes in the cognitive maps. In addition, the remembering of the cognitive map can be seen as a constructive task induced by the external stimuli, so that communication of spatial information will also transform the cognitive map. The changes in cognitive maps are divided into the following two levels of time scale: ontogenesis during the life-span of an individual, and microgenesis during a relatively short period.

Concerning the ontogenetic level, the developmental theory of Piajet suggests that the spatial framework of the cognitive map changes from an egocentric system of reference into a coordinated one, shifting its geometric forms from topological space to Euclidean space (Hart and Moore, 1973). In addition, the content of the cognitive map changes from the route map into the survey map (Siegel and White, 1975). As a result, cognitive maps become similar to the actual map with the increase of age. This tendency was revealed by the result for the Tokyo data, showing that cognitive maps of university students are more similar to the actual map than those of high school students.

As for the microgenesis, the cognitive map seems to change from route map into survey map, increasing its accuracy. Although little has been known about their mechanisms, the anchor point theory (Golledge, 1978a) become an influential model for this microgenetic process. This theory regards nodes and paths in the cognitive map as hierarchically organized according to their importance for life. This notion agrees with the hypothesis of the hierarchical structure in cognitive maps (Stevens and Coupe, 1978). However, as Spencer (1991) pointed out, the developmental process of environmental cognition is affected by the historical/cultural context as well as by individual differences. For this reason, Euclidean space should not be regarded as the final stage of this process (Golledge and Spector, 1978). Such a notion can be validated by the result of the present study that most of the cognitive maps for the university students who advanced to the final developmental stage of environmental cognition indicated non-Euclidean properties.

The factors causing fuzziness

The above discussion is concerned mainly with, what Gale (1982) calls, the distortion contained in the errors of cognitive maps. Concerning the fuzziness that is another component of these errors, the standard deviational ellipses for the peripheral locations tended to be greater than those for the central ones. This tendency can be explained by the information-processing model in the following two manners:

First, the difference in the acquisition of information from direct contact with the environment probably caused this. Specifically, the fuzziness for the peripheral locations becomes large because of the individual differences in visits to them, while that for the central locations becomes small because the subjects frequently visit there and have common information about them. Gale (1982) also reported the negative correlation between the ellipse areas and familiarity. This explanation, however, contradicts the fact that Locs. 7 and 8 adjoining the schools of the students of Tokyo-A and B indicated a great fuzziness (Fig. 9).

Another explanation can be provided from rotation heuristics by which the subjects encode the environmental information. Assuming that the cognitive map is conceptually rotated upon the central part of the study area, the amount of the shift in location becomes greater at peripheral points than at central ones. Thus, individual differences in rotated angle obviously appear at peripheral points. Nevertheless, it is not yet known whether the cognitive map is rotated upon the center of the configuration in the same way as the Euclidean transformation of least squares.

As described above, it is difficult for the analysis of the present study to give a satisfactory explanation to the fuzziness in cognitive maps. In order to discuss this, the fuzziness in an individual cognitive map has to be operationally separated from that in the aggregated one. Therefore, we ought to begin with the measurement of fuzziness in an individual cognitive map by employing such an algorithm as probabilistic MDS, PROSCAL (Mackay and Zinnes, 1981).

7. Conclusion

The author presented an integrated framework for the quantitative analysis of the spatial patterns in cognitive maps by means of the techniques of spatial analysis. This framework was applied to an empirical analysis of the data derived from the students in four Japanese cities. Then, the spatial patterns of cognitive maps were explained on the basis of the information-processing model. The results are summarized as follows:

The components of distortions were divided into the absolute and the relative ones (Lloyd, 1989) by the Euclidean transformation of least squares. The absolute distortion was analyzed by handling the data derived from sketch mapping in Hiroshima and Kanazawa. The directions of the cognitive maps deviated systematically from the actual one so as to adjust the reference lines, namely the river channels running across these cities, to cardinal directions; the cognitive distances tended to be overestimated (Figs. 6 and 7; Tables 2-5). These facts were explained by rotation/alignment heuristics (Tversky, 1981) and implicit scaling model (Holyoak and Mah, 1982).

The sketch maps and distance estimates in Tokyo and Sapporo were analyzed in terms of the relative distortion. The cognitive maps for three samples in Tokyo commonly showed a transformation of the Yamanote Line to a well-balanced form in a similar manner to the result obtained by Canter and Tagg (1975) (Fig. 9). This supports the reliability of the method used to extract the cognitive maps. As for the validity of the method, the subjects' self-evaluation of their cognitive configurations indicated that sketch mapping is superior in criterion-related validity.

The cognitive maps in Sapporo, however, indicated a somewhat different tendency in the methods for extracting them (Figs. 10 and 11; Table 12): the sketch maps showed a striking similarity with the actual map, but the configurations recovered from estimated distances were closely related to the route-distance space (Fig. 12). This tendency implies that the cognitive map contains the property of route map as well as that of survey map.

Another component of errors in cognitive maps, called fuzziness (Gale, 1982), was measured by standard deviational ellipses for each locations. The fuzziness of locational cognition was greater in peripheral places than in central ones within the study area (Tables 10 and 14).

The information-processing model provided us with an comprehensive explanatory framework for the spatial patterns in cognitive maps. According to this framework, the process of cognitive mapping was divided into the following six stages: acquisition of environmental information, encoding, storage, decoding, reproduction/usage, and transformation (Fig. 13). Although it gives a satisfactory explanation of the patterns of distortions, those of fuzziness were hard to explain. Therefore, the definition and method for analyzing fuzziness are open to further discussion.

Furthermore, the present study brought about some improvements in the analytical procedure. Specifically, the analysis of the data for Sapporo was carried out assuming the actual map to be an independent variable of the Euclidean regression. In addition, the meaning of "actual map" was extended to the configuration other than the cartographic map. The configuration of the route-distance space recovered from the distance matrix of the city-block metric by MDS was inputted to Euclidean regression as an explanatory variable, proving that the cognitive map obtained by distance estimation fits better for the route-distance space than for the cartographic map.

This result implies a non-Euclidean property of the cognitive map, which was also validated by the stress values of MDS being lowest for the city-block metric among three Minkowskian metrics (Tables 15 and 16). The non-Euclidean properties of cognitive maps have already been pointed out by Golledge and Hubert (1982). In addition, recent findings in cognitive science have negated the Euclidean nature of cognitive maps. For example, the effect of implicit scaling (Holyoak and Mah, 1982) on encoding process will cause asymmetrical distance estimates. Furthermore, the hierarchical storage of spatial information (Stevens and Coupe, 1978) will cause local distortions that cannot be detected by the Euclidean regression.

These facts requires further improvements in the methodology. Nevertheless, the Euclidean transformation used in the present study is easily carried out and it enables visual comparison between the cognitive and the actual maps. Considering that the method for analyzing non-Euclidean space has not yet been established, it would be valid for the time being to analyze cognitive maps within Euclidean space by means of MDS that can also represent the non-Euclidean in the Euclidean space.

Acknowledgements

This paper is a part of the doctoral thesis submitted to Tokyo Metropolitan University in 1993. The author wishes to thank Professor Yoshio Sugiura of the Department of Geography at Tokyo Metropolitan University for his constant advice and encouragement during the course of this work. He also acknowledges Professor Hiroshi Kadomura and Associate Professor Toshio Kikuchi of the Department of Geography and Professor Itsuki Nakabayashi of the Center for Urban Studies at the Tokyo Metropolitan University for reading the manuscript and making helpful advises.

Special thanks are due to Mr. Toshitsugu Tanaka (Towa Real-estate Development Co., Ltd.), Mr. Yoshihiko Suda (Keio High School) and Dr. Satoru Itoh (Kanazawa University) for permission to use the data collected in Hiroshima, Tokyo and Kanazawa respectively.

Finally, personal acknowledgements are due to the faculty members of the Department of Geography at Hiroshima University for their careful guidance and kind encouragement during the doctor's course, and to Associate Professor Keiji Yano of the Department of Geography at Ritsumeikan University and the members of the GRECO circle for fruitful discussions.

This research was supported in part by the Grant-in-Aid for Scientific Research from the Japanese Ministry of Education, Science and Culture (Nos. 63580190, 05780129 and 001714).

References Cited

Appleyard, D.(1969): City designers and the pluralistic city. In Rodwin, L. (ed.) "*Urban Growth and Regional Development.*" MIT Press, Cambridge, Mass., 422-452.

Baird, J.C., Merrill, A.A. and Tannenbaum, J.(1979): Studies of the cognitive representation of spatial relations, II: A familiar environment. *Journal of Experimental Psychology*, **108**, 92-98.

Briggs, R.(1976): Methodologies for the measurement of cognitive distance. In Moore, G. T. and Golledge, R.G. (eds.) "*Environmental Knowing.*" Dowden, Hutchinson & Ross, Strousbourg, 325-334.

Burgess, J. and Gold, J.R. (1985): Introduction: place, the media and popular culture. In Burgess, J. and Gold, J.R. (eds.) "*Geography, the Media and Popular Culture.*" Croom Helm, London, 1-32.

Buttenfield, B.P.(1986): Comparing distortion on sketch maps and MDS configurations. *Prof. Geogr.*, **38**, 238-246.

Cadwallader, M.T.(1977): Frame dependency in cognitive maps: an analysis using directional statistics. *Geogr. Anal.*, **9**, 284-292.

Canter, D. and Tagg, S.K.(1975): Distance estimation in cities. *Environ. and Behav.*, **7**, 59-80.

Cliff, N.(1966): Orthogonal rotation to congruence. *Psychometrika*, **31**, 33-42.

Couclelis, H., Golledge, R.G., Gale, N. and Tobler, W.(1987): Exploring the anchor point hypothesis of spatial cognition. *Journal of Environmental Psychology*, **5**, 99-122.

Day, R.A.(1976): Urban distance cognition: review and contribution. *Australian Geographer*, **13**, 193-200.

Downs, R.M.(1981a): Maps and metaphors. *Prof. Geogr.*, **33**, 287-293.

——(1981b): Cognitive mapping: a thematic analysis. In Cox, K. and Golledge, R.G. (eds.) "*Behavioral Problems in Geography Revisited.*" Methuen, London, 95-122.

——(1981c): Maps and mapping as metaphors for spatial representation. In Liben, L., Patterson, A. and Newcombe, N. (eds.) "*Spatial Representation and Behavior across the Life Span.*" Academic Press, New York, 143-166.

——and Stea, D.(1973): Cognitive maps and spatial behavior: process and products. In Downs, R.M. and Stea, D. (eds.) "*Image and Environment: Cognitive Mapping and Spatial Behavior.*" Aldine, Chicago, 8-26.

Evans, G.W. and Pezdek, K.(1980): Cognitive mapping: knowledge of real world distance and location. *Journal of Experimental Psychology: Human Memory and Learning*, **6**, 13-24.

Fujita, N., Loomis, J.M., Klatzky, R.L. and Golledge, R.G.(1990): A minimal representation for dead-reckoning navigation: updating the homing vector. *Geogr. Anal.*, **22**, 326-335.

Gaile, G.L. and Burt, J.E.(1980): *Directional Statistics*. CATMOG, Geo Abstracts, Norwich, 39p.

Gale, N.(1982): Some applications of computer cartography to the study of cognitive configurations. *Prof. Geogr.*, **34**, 313-321.

Gärling, T., Böök, A. and Linberg, E.(1984): Cognitive mapping of large-scale environments: the interrelationship of action plans, acquisition, and orientation. *Environ. and Behav.*, **16**, 3-34.

Gatrell, A.(1983): *Distance and Space*. Oxford UP, Oxford, 195p.

Gold, J.(1992): Image and environment: the decline of cognitive-behaviouralism in human geography and grounds for regeneration. *Geoforum*, **23**, 239-247.

Golledge, R.G.(1977): Multidimensional analysis in the study of environmental behavior and environmental design. In Altman, I. and Wohlwill, J.F. (eds.) "*Human Behavior and Environment: Advances in Theory and Research, Vol. 2.*" Plenum Press, New York, 1-42.

——(1978a): Learning about urban environment. In Carlstein, T., Parkes, D. and Thrift, N. (eds.) "*Timing Space and Spacing Time Vol. I: Making Sense of Time.*" Edward Arnold, London, 76-98.

——(1978b): Representing, interpreting, and using cognized environments. *Pap. Reg. Sci. Assoc.*, **41**, 169-204.

——(1991): Special populations in contemporary urban areas. In Hart, J.F. (ed.) "*Our Changing Cities.*" Johns Hopkins University Press, Baltimore, 146-169.

——, Briggs, R. and Demko, D.(1969): The configuration of distances in intra-urban space. *Proc. Assoc. Amer. Geogr.*, **1**, 60-65.

——, Gale, N., Pellegrino, J.W. and Doherty, S.(1992): Spatial knowledge acquisition by children: route learning and relational distance. *Ann. Assoc. Amer. Geogr.*, **82**, 223-244.

——and Hubert, L.J.(1982): Some comments on non-Euclidean mental maps. *Environ. and Plann. A*, **14**, 107-118.

——, Pellegrino, J.W., Gale, N. and Doherty, S.(1991): Acquisition and integration of route knowledge. *The National Geographical Journal of India*, **37**, 130-146.

——and Spector, A.(1978): Comprehending the urban environment: theory and practice. *Geogr. Anal.*, **10**, 403-426.

Goodchild, B.(1974): Class differences in environmental perception. *Urban Studies*, **11**, 157-169.

Graham, E.(1976): What is a mental map? *Area*, **8**, 259-262.

——(1982): Maps, metaphors and muddles. *Prof. Geogr.*, **34**, 251-260.

Hart, R.A. and Moore, G.T.(1973): The development of spatial cognition. In Downs, R.M. and Stea, D. (eds.) "*Image and Environment: Cognitive Mapping and Spatial Behavior.*" Aldine, Chicago, 246-288.

Hayashi, C. and Akuto, H. (eds.)(1976): *Tajigen Shakudo Kaisekiho: Sono Yukosei to Mondaiten (Multidimensional Scaling: Its Effectiveness and Problems).* Saiensu-sha, Tokyo, 290p.*

Hesse, M.B.(1970): *Models and Analogies in Science, 2nd ed.* Univ. of Nortre Dame Press, Indiana, 184p.

Holyoak, K.J. and Mah, W.A.(1982): Cognitive reference points in judgements of symbolic magnitude. *Cognitive Psychology*, **14**, 328-352.

Kanakubo, T.(1991): *Gendai Riron-chizugaku no Hattatsu (The Development of Contemporary Theoretical Cartography).* Taimeido, Tokyo, 311p.*

Kosslyn, S.M.(1981): The medium and the message in mental imagery: a theory. *Psychological Review*, **88**, 46-66.

Liben, L.(1981): Spatial representation and behavior: multiple perspectives. In Liben, L., Patterson, A., and Newcombe, N. (eds.) "*Spatial Representation and Behavior across the Life Span.*" Academic Press, New York, 3-36.

Lingoes, J.C. and Schönemann, P.H.(1974): Alternative measures of fit for the Schönemann-Carroll matrix fitting algorithm. *Psychometrika*, **39**, 423-427.

Lloyd, R.(1982): A look at images. *Ann. Assoc. Amer. Geogr.*, **72**, 532-548.

——(1989): Cognitive maps: encoding and decoding information. *Ann. Assoc. Amer. Geogr.*, **79**, 101-124.

——and Heivly, C.(1987): Systematic distortions in urban cognitive maps. *Ann. Assoc. Amer. Geogr.*, **77**, 191-207.

——and Steinke, T.(1976): The decision-making process for judging the similarity of choropleth maps. *The American Cartographer*, **3**, 177-184.

——and——(1977): Visual and statistical comparison of choropleth maps. *Ann. Assoc. Amer. Geogr.*, **67**, 429-436.

——and——(1984): Recognition of disoriented maps: the cognitive process. *The Cartographic Journal*, **21**(June), 55-59.

Lynch, K.(1960): *The Image of the City*. MIT Press, Cambridge, Mass., 194p.

MacEachren, A.M.(1992): Application of environmental learning theory to spatial knowledge acquisition from maps. *Ann. Assoc. Amer. Geogr.*, **82**, 245-274.

MacKay, D.B.(1976): The effect of spatial stimuli on the estimation of cognitive maps.

Geogr. Anal., 8, 439-452.

——, Olshavsky, R.W. and Sentell, G.(1975): Cognitive maps and spatial behavior of consumers. *Geogr. Anal.*, **7**, 19-34.

——and Zinnes, J.L.(1981): Probabilistic scaling of spatial distance judgements. *Geogr. Anal.*, **13**, 21-37.

Magana, J.R., Evans, G.W. and Rommney, A.K.(1981): Scaling techniques in the analysis of environmental cognition data. *Prof. Geogr.*, **33**, 294-301.

Moellering, H.(1980): Strategies of real-time cartography. *Cartographic Journal*, **17**, 12-15.

Murakoshi, S.(1987): Cognitive map and spatial behavior. *Shinrigaku Hyoron*, **30**, 188-207.**

Ohyama, T., Ikeda, H. and Mutoh, S. (1971): *Shinri Sokutei Tokei-ho (Psychological Measurement and Statistics)*. Yuhikaku, Tokyo, 278p.*

Okamoto, K.(1982): A review of cognitive distance studies. *Jimbun-Chiri (The Human Geography)*, **34**, 429-448.*

O'Keefe, J. and Nadel, L.(1978): *The Hippocampus as a Cognitive Map*. Oxford Univ. Press, New York, 570p.

Olshavsky, R.W., MacKay, D.B. and Sentell, G.(1975): Perceptual maps of supermarket locations. *Jour. of Applied Psychology*, **60**, 80-86.

Peuquet, D.(1988): Representations of geographic spaces: towards a conceptual synthesis. *Ann. Assoc. Amer. Geogr.*, **78**, 375-394.

Pocock, D.C.D. (1972): Perspective and urban perception, hypothesis and initial findings. *Architectural Psychology Newsletter*, **2**(4), (no page).

——(1973): Urban environmental perception and behaviour: a review. *Tijdschr. Econ. Soc. Geogr.*, **64**, 251-257.

——(1976): Some characteristics of mental maps: an empirical study. *Trans. Inst. Brit. Geogr., N.S.*, **1**, 493-512.

——(1978): The cognition of intra-urban distance, a summary. *Scot. Geogr. Magazine*, **94**, 31-35.

Richardson, G.D.(1981a): The appropriateness of using various Minkowskian metrics for representing cognitive configurations. *Environ. and Plan. A*, **13**, 475-485.

——(1981b): Comparing two cognitive mapping methodologies. *Area*, **13**, 325-331.

Robinson, M.E. and Dicken, P.(1979): Cloze procedure and cognitive mapping. *Environ. and Behav.*, **11**, 351-373.

Robinson, A.H., Sale, R.D. and Morrison, J.(1978): *Elements of Cartography, 4th ed.* John Wiley & Sons, New York, 448p.

Schönemann, P.H. and Carroll, R.M.(1970): Fitting one matrix to another under choice of a central dilation and a rigid motion. *Psychometrika*, **35**, 245-255.

Self, C.M., Gopal, S., Golledge, R.G. and Fenstermaker, S.(1992): Gender-related differences in spatial abilities. *Progr. in Hum. Geogr.*, **16**, 315-342.

Sherman, R.C., Croxton, J. and Giovanatto, J.(1979): Investigating cognitive representations of spatial relationships. *Environ. and Behav.*, **11**, 209-226.

Shiba, S.(1979): *Inshibunseki-ho, Dai 2-han (Factor Analysis, 2nd ed.)*. University of Tokyo Press, Tokyo, 298p.*

Siegel, A.W.(1981): The externalization of cognitive maps by children and adults: in search of ways to ask better questions. In Liben, L., Patterson, A., and Newcombe, N. (eds.) "*Spatial Representation and Behavior across the Life Span.*" Academic Press, New York, 167-194.

——and Cousins, J.H,(1985): The symbolizing and symbolized child in the enterprise of cognitive mapping. In Cohen, R. (ed.) "*The Development of Spatial Cognition.*" Lawrence Erlbaum Assoc. Publishers, Hillsdale, New Jersey, 347-368.

——and White, S.H.(1975): The development of spatial representations of large-scale environments. In Rees, H.W. (ed.) "*Advances in Child Development and Behavior Vol. 10.*" Academic Press, New York, 9-55.

Spencer, C.(1991): Life-span changes in activities, and consequent changes in the cognition and assessment of the environment. In Gärling, T. and Evans, G. (eds.) "*Environment, Cognition, and Action: An Integrated Approach.*" Oxford University Press, New York, 295-308.

Steinke, T. and Lloyd, R.(1983): Image of maps: a rotation experiment. *Prof. Geogr.*, **35**, 455-461.

Stevens, A. and Coupe, P.(1978): Distortions in judged spatial relations. *Cognitive Psychology*, **10**, 422-437.

Sugiura, Y.(1985): Toshi-chirigaku ni okeru kukan-bunseki no kin'nen no tenkai (Recent development of spatial analysis in urban geography). In Tanabe, K. and Watanabe, Y. (eds.) "*Sokan Chirigaku Koza, 16: Toshi-chirigaku (Synoptic Geography Series, 16: Urban Geography).*" Asakura Shoten, Tokyo, 204-219.*

——(1990): Recent progress in MDS cognitive mapping. *Riron-Chirigaku Noto (Notes on Theoretical Geography),* **No. 7**, 45-65.*

Takahashi, J.(1972): Chiri-teki imeji to ningen kodo (Geographical image and human behavior). *Mita Journal of Economics*, **65**(11), 52-62.*

Takane, Y.(1980): *Tajigen Shakudo-ho (Multidimensional Scaling).* University of Tokyo Press, Tokyo, 332p.*

Tanaka, T. and Wakabayashi, Y.(1985): The students' cognition of distance and direction in Hiroshima City. *Chiri-Kagaku (Geographical Sciences),* **40**, 154-167.**

Thompson, D.L.(1963): New concept: subjective distance. *Journal of Retailing*, **39**, 1-6.

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

Tobler, W.(1965): Computation of the corresponding of geographical patterns. *Pap. Reg. Sci. Assoc.*, **15**, 131-139.

——(1976): The geometry of mental maps. In Golledge, R.G. and Rushton, G. (eds.) "*Spatial Choice and Spatial Behavior.*" Ohio State Univ. Press, Columbus, 69-81.

——(1983): *Bidimensional Regression: a Computer Program.* Discussion Paper, Dept. of Geography, Univ. of California, Santa Barbara, 72p.

Tolman, E.(1948): On cognitive maps in rats and men. *Psychological Review*, **55**, 189-208.

Trowbridge, C.C.(1913): On fundamental methods of orientation and 'imaginary maps.' *Science*, **38**, 888-897.

Tulving, E.(1983): *Elements of Episodic Memory*. Oxford UP, New York, 362p.

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

Upton, G.J.G. and Fingleton, B.(1989): *Spatial Data Analysis by Example Vol. 2: Categori-*

cal and Directional Data. John Wiley & Sons, Chichester, 416p.

Wakabayashi, Y.(1989a): Conceptual problems in cognitive map research. *Riron-Chirigaku Noto (Notes on Theoretical Geography)*, **No. 6**, 1-15.*

——(1989b): A quantitative analysis of distortions in cognitive maps. *Geographical Review of Japan*, **62A**, 339-358.**

——(1990a): Rethinking distortions in cognitive maps of Yamanote-line. *Riron-Chirigaku Noto (Notes on Theoretical Geography)*, **No. 7**, 1-19.*

——(1990b): Relative distortions in cognitive maps in Sapporo. *Geographical Review of Japan*, **63A**, 255-273.**

——(1991): A note on quantitative methods for analyzing distortions in cognitive maps. *Studies and Essays: History, The Faculty of Letters, Kanazawa University*, **No. 11**, 1-36.*

Waterman, S. and Gordon, D.(1984): A quantitative-comparative approach to analysis of distortion in mental maps. *Prof. Geogr.*, **36**, 326-337.

(*: in Japanese, **: in Japanese with English abstract)

APPENDIX A An example of the questionnaire sheet used to obtain distance estimations.

Question:

Imagine the map of Tokyo. Suppose that below the thick line represents the distance from Shibuya to Jiyugaoka. Please mark on the thin line how far it would be from the left side station to the right side stations, according to the example.

Example:

Yokohama ——————————|————|——————————|——————

Kawawsaki Kamakura Odawara

Kamakura
Odawara
Kawasaki

Shibuya ———————— Jiyugaoka

Tokyo ______________________________

Shinagawa
Shibuya
Shinjuku
Ikebukuro
Ueno
Jiyugaoka

Shibuya ———————— Jiyugaoka

Shinagawa ______________________________

Shibuya
Shinjuku
Ikebukuro
Ueno
Jiyugaoka

Shibuya ———————— Jiyugaoka

Shibuya ______________________________

Shinjuku
Ikebukuro
Ueno

Shibuya ———————— Jiyugaoka

Shinjuku ______________________________

Ikebukuro
Ueno
Jiyugaoka

Shibuya ———————— Jiyugaoka

Ikebukuro ______________________________

Ueno
Jiyugaoka

Shibuya ———————— Jiyugaoka

Ueno ______________________________

Jiyugaoka

APPENDIX B An example of the questionnaire sheet used to obtain sketch maps.

Question:

Suppose the dots below represent the locations of Shibuya and Jiyugaoka stations. Please indicate the remaining five locations by placing their names on the sheet. Take note that the vertical axis of the sheet does not necessarily correspond with the north–south line.

Stations to be placed: **Tokyo, Shinagawa, Shinjuku, Ikebukuro, Ueno**

● Shibuya

● Jiyugaoka

APPENDIX C An example of the questionnaire sheet used to obtain estimated distance in rating scale.

Question:

How far apart do you feel the places listed below are? Search through all the listed pairs of places and choose the pair that you feel is nearest apart, marking the score of "1". Next, choose the pair that you feel is farthest apart, marking it with the score of "9." After that, please mark the scores between "2" and "8" for the remaining pairs according to how far apart you feel the places are.

Example: *near* ← → *far*

Tokyo — Yokohama 1 2 3 4 5 6 [✓ 7] 8 9

Tokyo — Shinagawa 1 2 3 4 5 6 7 8 9
Tokyo — Shibuya 1 2 3 4 5 6 7 8 9
Tokyo — Shinjuku 1 2 3 4 5 6 7 8 9
Tokyo — Ikebukuro 1 2 3 4 5 6 7 8 9
Tokyo — Ueno 1 2 3 4 5 6 7 8 9
Tokyo — Jiyugaoka 1 2 3 4 5 6 7 8 9
Shinagawa — Shibuya 1 2 3 4 5 6 7 8 9
Shinagawa — Shinjuku 1 2 3 4 5 6 7 8 9
Shinagawa — Ikebukuro 1 2 3 4 5 6 7 8 9
Shinagawa — Ueno 1 2 3 4 5 6 7 8 9
Shinagawa — Jiyugaoka 1 2 3 4 5 6 7 8 9
Shibuya — Shinjuku 1 2 3 4 5 6 7 8 9
Shibuya — Ikebukuro 1 2 3 4 5 6 7 8 9
Shibuya — Ueno 1 2 3 4 5 6 7 8 9
Shibuya — Jiyugaoka 1 2 3 4 5 6 7 8 9
Shinjuku — Ikebukuro 1 2 3 4 5 6 7 8 9
Shinjuku — Ueno 1 2 3 4 5 6 7 8 9
Shinjuku — Jiyugaoka 1 2 3 4 5 6 7 8 9
Ikebukuro — Ueno 1 2 3 4 5 6 7 8 9
Ikebukuro — Jiyugaoka 1 2 3 4 5 6 7 8 9
Ueno — Jiyugaoka 1 2 3 4 5 6 7 8 9