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Mapping Regional Settlement in Information Space

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Determining patterns of settlement interaction in the absence of direct evidence is an important consideration in regionally oriented archaeological inquiry. In the following study we introduce the concepts of alternative spaces, and transformed map representations of these spaces, as possible approaches to this problem. The southern Basin of Mexico is examined as a particular case in point, with settlement pattern maps developed in travel time space for the Late Formative through Late Toltec occupations in this region. Through arranging sites in terms of their accessibility to one another, such maps provide a foundation for systematically proposing groups of interacting settlements in each time period examined. The proposed patterns of spatial affiliation are used to explore the role of information processing in the sociopolitical evolution of the southern basin. © 1990 Academic Press, Inc.

INTRODUCTION

Of the several areas of analytical inquiry that have attracted the attention of archaeologists over the past several years, one of the most widely endorsed concerns the spatial analysis of archaeological data. This research emphasis appeals to the fundamental nature of human behavior; simply stated, the remains of past peoples, both at regional scales (Hodder and Orton 1976; Johnson 1977) and at scales restricted to the area within the site or within the household (Carr 1984), *always* occur in space—just as all modern activity does. In attempting to understand the spatial behavior of the past, archaeologists often turn to human geography, where spatial problems are of primary concern. But as geographers have discovered, the notion of *space* is replete with underlying meaning. Often it is within the complexity of this hidden meaning that the most important insights on spatial behavior may be found.

In the following essay we examine select aspects of space in the context of past regional organization in the southern Basin of Mexico (Fig. 1). Data on past regional adaptation in this area have been collected through a series of intensive archaeological surveys. The results of these surveys are published (Parsons 1971; Blanton 1972; Parsons et al. 1982; 1983),

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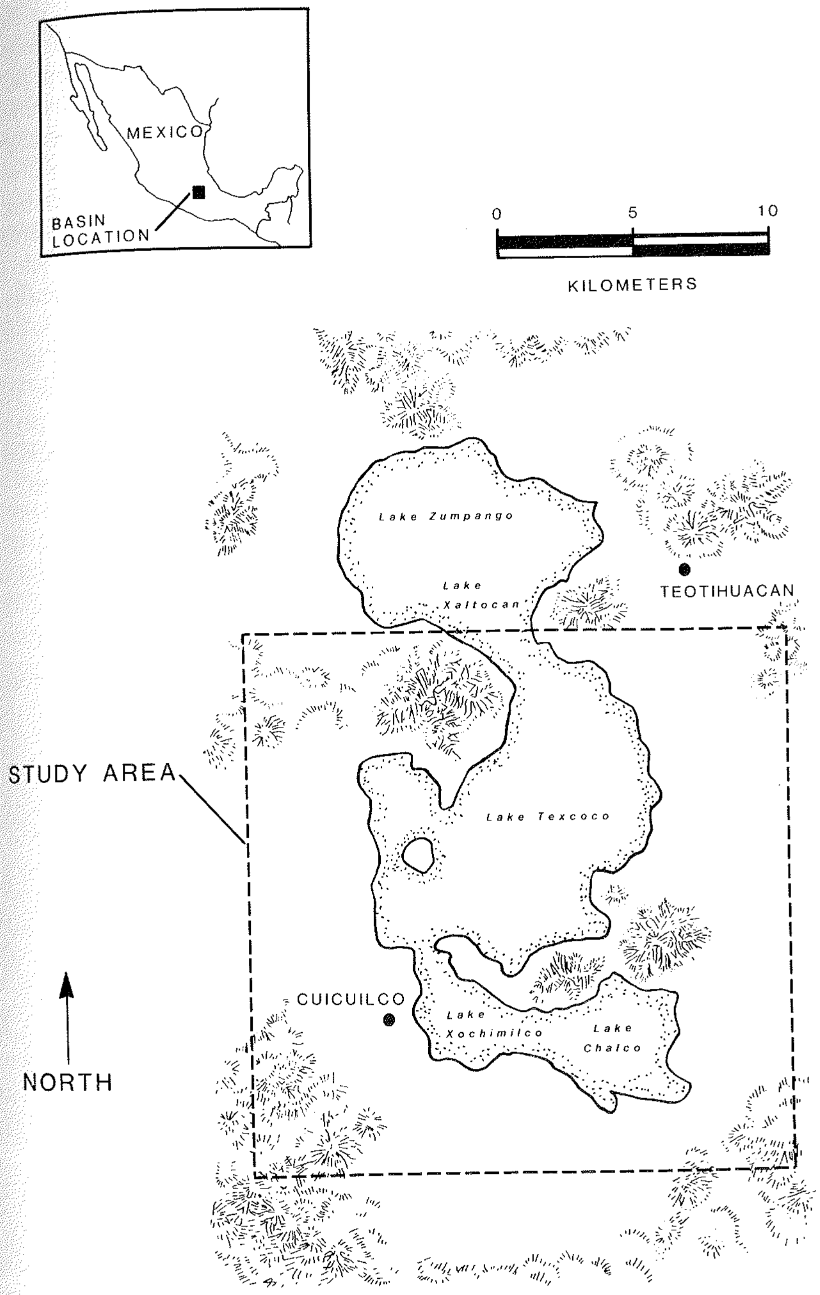

FIG. 1. The southern Basin of Mexico.

providing a remarkably detailed picture of prehispanic settlement in the southern basin as it evolved over time.[1,*] Examinations of regional organization often must deal with the question of settlement interaction, particularly where complex societies which incorporate several communities are concerned. In the southern Basin of Mexico, the frequently undulating terrain and central lake system would have presented major challenges to the spatial integration of separate communities. To understand better the nature of these challenges, and their effect on regional settlement, we transform the geographic space of the southern basin into a space which is based upon *travel time* between places. Such a transformation arranges settlements in terms of their relative accessibility to one another, and thus provides a foundation for proposing clusters of interacting sites. These patterns of spatial interaction, in turn, enable the examination of several important anthropological questions; in the pages following we explore one of the most fundamental of these questions, namely the role of information processing in sociopolitical evolution.

SOME METHODOLOGICAL NOTES

Relative Spaces and Travel Time

One of the most important developments in human geography in recent years has been the emergence of *relative space* as a perspective for the study of human spatial behavior. Geographers now widely recognize that the spatial context of many human activities cannot fully be described in terms of the physical, Euclidian distance measures associated with absolute space. Studies in a number of different contexts suggest that "real" space is as much a product of economic, social, cultural, and psychological considerations as it is of physical composition (cf. Watson 1955; Hägerstrand 1957; Bunge 1966:53–60, 179–187; Muller 1978; Gatrell 1983:43–80). Spaces which incorporate such considerations may be defined by employing appropriate measures of separation or proximity.[2] One of the most instructive means of studying alternative spaces is through their representation as transformed maps, arranging various places in terms of the proximity measure of interest. The work of Tobler (1961) in particular has been instrumental in providing the mathematical and computer cartographic means of developing such maps.

The present study employs travel time as a basis for depicting spatial relationships in a regional context. This choice is based upon a very simple proposition: in cases where settlement interaction requires the movement of individuals between places, spatial separation is represented more accurately by travel time than Euclidian distance. For example, two settlements situated very close to one another in geographic space, but separated by a rugged mountain range, may have more difficulty interacting with each other than with a third settlement located at a greater geographic distance over more easily negotiated terrain. In such a case, depicting the mutual proximity of settlements simply in terms of geographic separation is misleading if one is interested in their potential for interaction.

In focusing upon travel time, we do not wish to imply that this is the only way in which to view spatial relationships. Nevertheless, this measure of separation has proven useful in several geographic research settings. In the context of individual behavior, travel time appears to be one of the predominant measures of proximity used by individual decision makers, both to assess distances between places and to guide their spatial activities (Cadwallader 1976; Burnett 1978; MacEachren 1980). In the context of regional geography, researchers have shown that an area's regional organization experiences fundamental changes as developments in transportation modify its travel time space (Marchand 1973; Clark 1977). Recently, travel time has been proposed as a basis for regional transportation in the northeastern Basin of Mexico during the late prehispanic–early Colonial occupation (Gorenflo 1990). Results from the latter study suggest that during a period of occupation in the basin when regional efficiency would have been particularly important the transportation network present enabled close-to-minimal travel time movement between places. These examples of previous research help to support the proposition that travel time is a useful measure of proximity, largely as an indicator of *spatial accessibility*. Moreover, in the absence of modern communication systems, conveying information between places would have occurred primarily through individuals carrying messages. In such a setting a space defined upon travel time thus provides insights on information flow—leading to the notion that travel time space might also be considered *information space*.

The first step in producing maps in travel time space is to obtain data on the time it takes to move between various places. Detailed evidence for actual travel times in the southern Basin of Mexico during prehispanic periods of occupation of course is unavailable. But one can acquire other types of information which enable the systematic *estimation* of travel times. In the absence of beasts of burden, human movement in this setting would have taken place over land by foot, over water by canoe, or in some combination of the two. Furthermore, for long trips it is unlikely that people in general traveled constantly day and night, instead breaking their journeys into shorter segments and resting at night. Thus, for the

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* See Notes section at end of paper for all footnotes.

purpose of estimating travel times between places in the prehispanic basin one must consider three different situations: (1) travel velocity on land, (2) travel velocity on water, and (3) travel overnight.

In the first case, the speed with which people travel by foot over land tends to be a function of the slope of terrain. A formula calibrated from empirical data on soldiers hiking in various types of topography enables the estimation of walking velocities for different slopes (Tobler, personal communication; cf. Imhof 1968):

$$v = 6\,e^{-3.5\,|s\,+\,.05|},$$

where
v is walking speed,
s is the slope of terrain (calculated as vertical change divided by horizontal change), and
e is the base for natural logarithms.

This function is symmetric, but slightly offset from a slope of zero. The estimated velocity is greatest when walking down a slight decline, with velocities reduced at lessening rates both for decreases and increases in the slope negotiated.

Dugout canoes were used to travel across the central lake system in the Basin of Mexico at the time of Spanish conquest, and we shall assume they were used during the time periods examined in this study as well. These canoes had to be poled or paddled constantly in the absence of any appreciable current, their movements often restricted to corridors cleared in the lake reeds (Gibson 1964:364). Spanish comments about canoe travel in the basin during the early sixteenth century suggest that this mode of transportation was about one-third slower than travel by foot over level ground (Cortés 1908:67–69; cf. Alden 1979:174; Hassig 1985:64). This produces an average velocity of 3.33 km/hr when traveling over water.

Finally, for long journeys we shall assume that trips of 8 hr were the maximum duration traveled on average in a single day. This value is slightly greater than the daily average of 6 hr traveled by professional Aztec burden carriers (Sanders and Santley 1983:246), allowing for slightly increased trip duration due to an assumed reduction in the weights carried. Eight hours of actual travel would enable a long day's journey during daylight hours, with sufficient time remaining to arrange for necessities such as food and lodging. For each trip exceeding 8 hr, therefore, an additional 8 hr of rest time is added to its duration. No point in the study area is estimated to be more than 17 hr actual travel from any other point.

We employed the above three principles to estimate the travel times between a set of locations in the southern Basin of Mexico. To provide systematic coverage of the study area, travel times were calculated on a 5 × 5-km grid of 25 sample points placed over the area of interest. To ensure complete coverage of this area, estimates were generated for travel between each point and all 24 others. Working with a 50-m contour map, travel times were calculated for 1-km intervals, and then summed as appropriate to connect sample points. On the assumption that interaction between settlements would involve movement in both directions, the two estimates for each pair of points were averaged to provide a single travel time value.

Transforming Maps into Travel Time Space: Trilateration and Bidimensional Regression

Given a collection of estimated travel times between several locations, the problem now becomes one of finding a configuration of points such that the distance between each pair matches their travel time separations as nearly as possible. Probably the best known method for approaching this task is multidimensional scaling (cf. Golledge and Rushton 1972; Kruskal and Wish 1978). A less familiar alternative is Tobler's trilateration procedure—the method employed here because of its wider range of graphic results, providing greater insights to the nature of the relative space concerned. Because technical descriptions of this and the other methods used below to produce settlement maps in travel time space are not widely published, we briefly outline their main characteristics in the following pages.

Denoting the travel time separating points i and j as d_{ij}, the problem faced here is one of finding a set of coordinates which minimizes the quantity $\Sigma\ (d_{ij} - d_{ij}^*)$, where d_{ij}^* is the Euclidian distance between the new coordinates of i and j. In other words, we want the new set of interpoint distances d_{ij}^* to represent the travel time distances d_{ij} with the minimal amount of overall error. Trilateration is an iterative procedure, employing resultant vectors based upon d_{ij} values, which adjusts a configuration of points such that $\Sigma\ (d_{ij} - d_{ij}^*)$ is reduced at each iteration. The algorithm and key formulae for this procedure may be found in Appendix I.

Once a travel time configuration of points is obtained, one must develop a map in travel time space. Here we employ a technique for comparing two planar configurations of points (Tobler 1977, 1978), a method of *bidimensional regression* based on the classic work of Thompson (1917). This is organized in a manner analogous to simple linear regression, and solved via a procedure which minimizes the (squared) difference between the actual configuration of points and the configuration predicted by the methodology. However, instead of exploring the relationship between an independent and dependent variable which comprise single observations, the variables of interest comprise pairs of observations. Given a dependent variable W, consisting of observations in the form (u, v), and an independent variable Z, consisting of observations in the form (x, y), the mapping $Z \rightarrow \hat{W}$, or $(x,y) \rightarrow (\hat{u},\hat{v})$, in the simple Euclidian case can be written

$$\begin{bmatrix}\hat{u}\\ \hat{v}\end{bmatrix} = \begin{bmatrix}\alpha_1\\ \alpha_2\end{bmatrix} + \begin{bmatrix}\beta_{11} & -\beta_{12}\\ \beta_{12} & \beta_{11}\end{bmatrix}\begin{bmatrix}x\\ y\end{bmatrix}.$$

Here the least-squares problem becomes one of estimating the parameters α_1, α_2, β_{11}, and β_{12} such that the quantity

$$(1/n)\ \Sigma[(u_i - \hat{u}_i)^2 + (v_i - \hat{v}_i)^2)]$$

is minimized.

A more general linear relation may be defined by the following *affine transformation:*

$$\begin{bmatrix}\hat{u}\\ \hat{v}\end{bmatrix} = \begin{bmatrix}\alpha_1\\ \alpha_2\end{bmatrix} + \begin{bmatrix}\beta_{11} & \beta_{12}\\ \beta_{21} & \beta_{22}\end{bmatrix}\begin{bmatrix}x\\ y\end{bmatrix}.$$

This is of particular interest because of its capacity to handle nonlinear transformations, within which linearity is incorporated as a special case. In simple unidimensional linear regression, the slope is defined as $\Delta\hat{y}/\Delta x$. In the analogous unidimensional curvilinear case, the slope at any point on a function can be defined by the derivative $\partial\hat{y}/\partial x$. Moving to two dimensions, the nature of a curvilinear transformation can be approximated by the local derivatives, of which there are four at each point:

$$\frac{\partial\hat{u}}{\partial x}, \frac{\partial\hat{u}}{\partial y}, \frac{\partial\hat{v}}{\partial x}, \frac{\partial\hat{v}}{\partial y}.$$

Thus the matrix of β coefficients for the linear affine model becomes

$$\begin{bmatrix}\dfrac{\partial\hat{u}}{\partial x} & \dfrac{\partial\hat{u}}{\partial y}\\[2ex] \dfrac{\partial\hat{v}}{\partial x} & \dfrac{\partial\hat{v}}{\partial y}\end{bmatrix}$$

in the nonlinear case. In this manner, any differentiable transformation may be viewed as the conjunction of an infinite number of local transformations (Tobler 1977:12–13). We employ the more general, nonlinear affine model to transform geographic space into travel time space in the southern Basin of Mexico.

By using estimates of bidimensional regression parameters one can predict values of the coordinates $(\hat{u},\hat{v})$ given values of coordinates (x,y). In conjunction with the results of the aforementioned trilateration procedure itself, these estimated points help to produce a series of graphic illustrations which convey the nature of transforming one space into another. In Fig. 2, the arrows (*displacement vectors*) represent the discrepancies between the original configuration of geographic space and the configuration of travel time space after a least-squares Euclidian fit. Interpolation yields the generalized vector field of discrepancies in Fig. 3. And the orthogonal square lattice corresponding to the original space may be redrawn to represent the transformation as a warped grid (Fig. 4). We use this transformed grid below to plot the locations of settlements in travel time space.

INFORMATION SPACE IN THE PREHISPANIC SOUTHERN BASIN OF MEXICO

Having produced a representation of travel time space in the southern Basin of Mexico, we now examine configurations of settlement within it. As stated above, the arrangement of sites in such a space provides a more

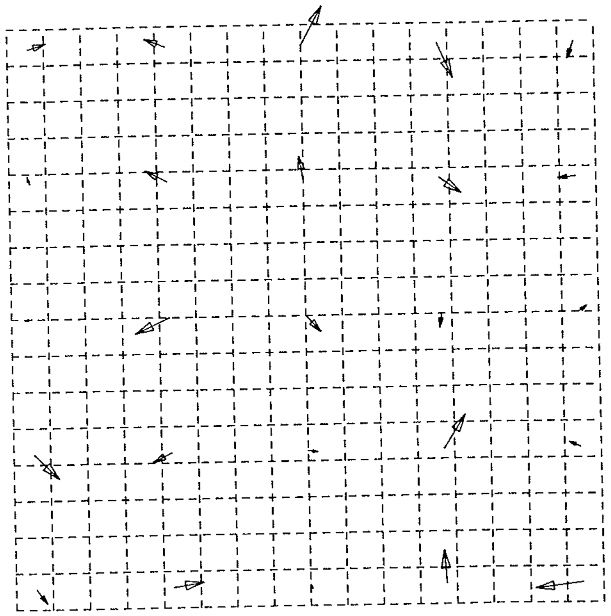

FIG. 2. Displacement vectors between sample points in geographic space and their respective locations in travel time space, in the southern Basin of Mexico.

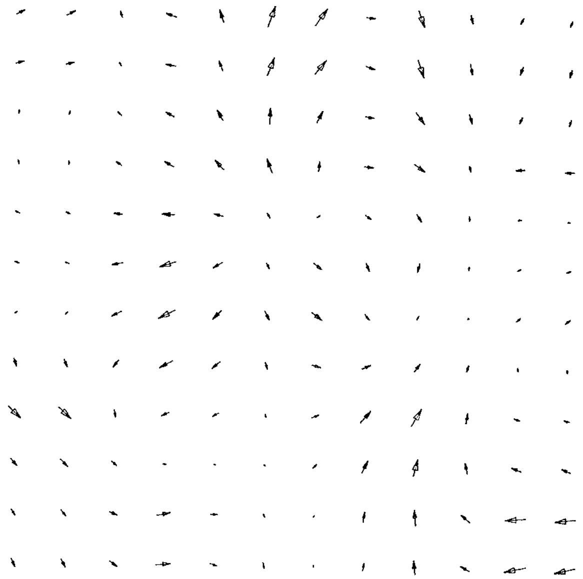

FIG. 3. Interpolated field of displacement vectors, resulting from the transformation of geographic space into travel time space, in the southern Basin of Mexico.

functional basis for proposing patterns of settlement interaction and, ultimately, information exchange. We examine these spatial patterns in order to evaluate the role of information processing in the evolution of sociopolitical hierarchies.

Before discussing the transformed settlement patterns themselves, let us make some brief observations about travel time space in the southern basin. The interpolated vector field (Fig. 3) and warped grid of travel time space (Fig. 4) are particularly useful in this task. Two characteristics of the transformation from geographic space to travel time space are noteworthy. To begin with, in general the changes resulting from this transformation are not great. As will be seen below, the corresponding shifts in settlement location likewise tend to be relatively slight, though in several instances they seem to represent adjustments toward locational regularity. Second, the most obvious modification due to the transformation is an expansion of the central portion of the study area—corresponding to the lake system, and the relatively slow movement associated with canoe travel. In particular, this central *stretching* underscores how inaccessible one side of the lake was from the other during prehispanic times.[3]

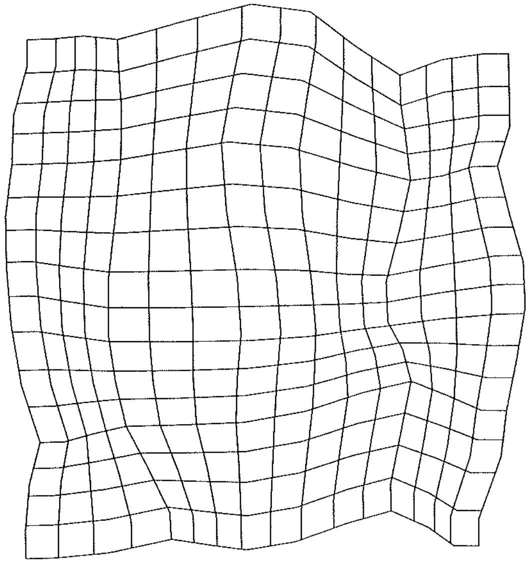

FIG. 4. "Warped" grid of travel time space, in the southern Basin of Mexico.

For the purpose of proposing patterns of interaction and information exchange, we focus upon transformed settlement patterns from five periods of occupation in the southern Basin of Mexico: the Late Formative, Terminal Formative, Classic, Early Toltec, and Late Toltec (Table 1).[4] Considered together, these five periods of prehistory encompass a wide range of sociopolitical change in the study area. For each period of interest, we plot settlements both in their original geographic locations and in travel time space. Two conventions are employed in constructing these maps. First, because our ultimate interest concerns information processing within a regional settlement system, we simplify the original site typology proposed for the prehispanic Basin of Mexico (Sanders et al. 1979:55–56) to focus solely upon levels in the administrative hierarchy. Most notably, the four types of villages (small dispersed, large dispersed, small nucleated, and large nucleated villages) are all treated as administratively equivalent. Similarly, although we preserve the distinction between provincial centers and regional centers on the settlement maps, we accord them identical administrative roles with regard to subservient sites.[5] The result of these assumptions is a three-tiered hamlet–village–center administrative hierarchy. On occasion fourth level centers were present in the basin during different phases of its prehistory—including, probably, the Terminal Formative and Classic periods. But because these centers were not located in the study area, we do not consider the fourth tier of information processing.

The second convention employed in producing transformed settlement pattern maps concerns the definition of *spatial aggregations* of sites. Drawing upon the notion that settlements in travel time space are ar-

TABLE 1

		MAJOR ARCHAEOLOGICAL PERIOD			ARCHAEOLOGICAL PHASE	PHASES FOCUS YEAR
YEARS A.D.	1200-	SECOND INTER-MEDIATE		EARLY POST-CLASSIC		
	1100-		PHASE TWO		MAZAPAN	"LATE TOLTEC"
	1000-		PHASE ONE		COYO-TLATELCO	"EARLY TOLTEC"
	900-					
	800-					
	700-	MIDDLE HORIZON	PHASE TWO	CLASSIC		
	600-				XOLALPAN	"CLASSIC"
	500-		PHASE ONE			
	400-					
	300-	FIRST INTER-MEDIATE				
	200-					
	100-			TERMINAL FORMATIVE		
	--0--					
YEARS B.C.	100-		PH. THREE-B		CUICUILCO V	"TERMINAL FORMATIVE"
	200-		PH. THREE-A		CUICUILCO VI	
	300-		PHASE TWO-B	LATE FORMATIVE	TICOMAN III	"LATE FORMATIVE"
	400-				TICOMAN II	
	500-					
	600-		PHASE TWO-A		TICOMAN I	
	700-					

ranged in terms of their relative accessibility to one another, we define two types of spatial aggregation. A *first level aggregation* focuses upon the affiliation of hamlets with higher-order settlements. Here we associate each hamlet with the higher-order settlement that is closest in travel time space. Thus a hamlet which is most accessible to a particular village is linked administratively to that village, while another hamlet which is most accessible to a particular center is linked administratively to it. A *second level aggregation,* in turn, focuses upon the affiliation of villages with higher-order settlements—in this case, centers. Once again, association is based upon proximity in travel time space, linking each village administratively to the most accessible center. In the process of defining a second level aggregation, all hamlets previously assigned to a village in the first level aggregation are carried along as "village aggregates," and thus ultimately also assigned to a particular center.

We begin our discussion of transformed settlement locations with the Late Formative (First Intermediate Phase II; 650–300 B.C.) period of occupation. This period was characterized by a substantial increase in population from the preceding Middle Formative, and provides the first evidence of a three-tiered settlement hierarchy in the Basin of Mexico (Sanders et al. 1979:97–98). The emergence of this hierarchy is thought to indicate the development social ranking and centralized political authority in the southern basin (Sanders 1981:172). Despite the presence of numerous villages and hamlets throughout the study area, much of the population during the Late Formative period resided in centers. The geographic patterning of sites during this period has been interpreted by other researchers as three clusters of settlement in the southern Basin of Mexico: in the northeastern portion of the study area (the lower-middle piedmont of the Texcoco region), in the southeastern portion of the study area (on the edges of the deep soil alluvium east of Lake Chalco), and in the south-central portion of the study area (on the northern and southern lake shores near the junction of Lakes Xochimilco and Chalco; Sanders et al. 1979:98).

Maps of both the original geographic pattern and the transformed travel time pattern of Late Formative settlement are presented in Fig. 5. The transformed map, coupled with the systematic aggregation of sites based upon accessability, suggests the presence of five settlement clusters organized around centers: in the northeastern portion of the study area (the lower-middle piedmont of the Texcoco region), in the central portion of the study area (the alluvium, and lower and middle piedmont, east of Lake Texcoco and northeast of Lake Chalco), in the southwestern portion of the study area (the alluvium, and lower and middle piedmont, primarily in the western Ixtapalapa Peninsula), in the central southeastern portion of the study area (the alluvium, and lower and middle piedmont east of Lake Chalco), and in the far southeastern portion of the study region (the middle and upper piedmont southeast of Lake Chalco). In addition to proposed patterns of settlement interaction, we note two characteristics in the travel time map. One is a tendency for hamlets which are located near one another in geographic space to bunch very close together in travel time space—a phenomenon for which we offer a possible explanation below. A second tendency in the travel time map, less obvious than the first, is the locational adjustment of several villages and centers

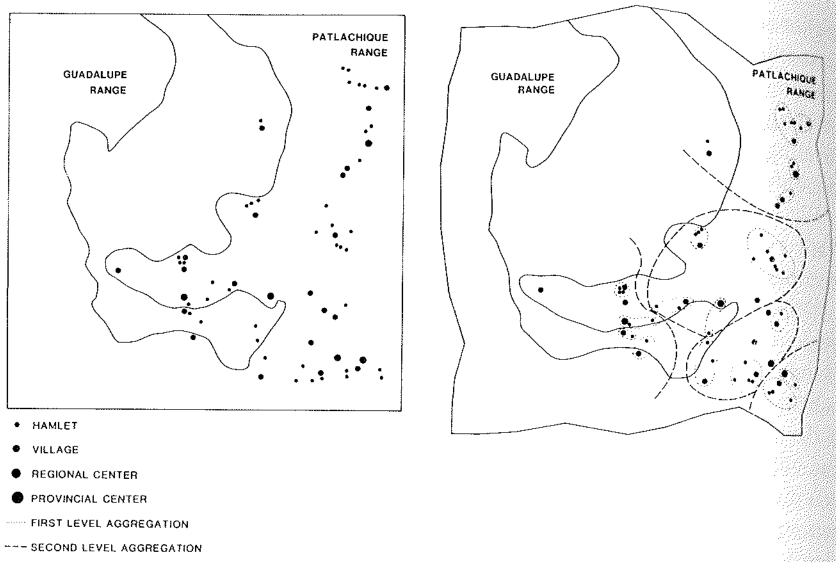

FIG. 5. Late Formative settlement, in geographic space and travel time space, in the southern Basin of Mexico. Left, original; right, transformed.

to establish relatively equivalent spacing between neighboring villages and centers. Both of these trends persist, to a greater or lesser degree, in the travel time maps for the succeeding four periods examined as well.

The next phase of occupation examined is the Terminal Formative period (First Intermediate, Phase III; 300–100 B.C.). This was a period of striking regional change throughout the Basin of Mexico, characterized by continued population growth and the emergence of large regional centers at Cuicuilco and Teotihuacan (Sanders et al. 1979:98–102). The nature of settlement in the basin as a whole may indicate the presence of two very complex chiefdoms (as defined by Service, 1971). Although neither of the two main centers were located within the present study area, they undoubtedly exerted an influence upon it—requiring that we keep their presence in mind while examining patterns of Terminal Formative settlement. A number of smaller sites occurred throughout the southern basin, in all likelihood ultimately subservient to either Cuicuilco or Teotihuacan. A three-tiered settlement hierarchy continued in this area during the Terminal Formative period. Previous researchers have suggested the presence of three groups of sites in the southern basin during this period, separated by areas of sparse occupation: in the east-central portion of the study area (the lower-middle piedmont of the Texcoco region), in the southeastern portion of the study area (the Chalco region) and in the south-central portion of the study area (the Ixtapalapa region and northern Xochimilco region; Sanders et al. 1979:102). The transformed map for the Terminal Formative indicates the presence of nine clusters of settlement: two in the northeastern portion of the study area (the lower and middle piedmont of the northern Texcoco region, east of Lake Texcoco), two in the eastern portion of the study area (east of Lake Texcoco, one in the alluvium and lower piedmont, one in the lower and middle piedmont), one in the southwestern portion of the study area (the alluvium, lower piedmont, and middle piedmont of the Ixtapalapa Peninsula and southern shore of Lake Xochimilco), and four in the southeastern portion of the study area (two in the alluvium, and lower and middle piedmont, on the northeastern and eastern shores of Lake Chalco, and two predominantly in the middle and upper piedmont east of Lake Xochimilco; Fig. 6).

The Classic period of occupation (limited here to the Middle Horizon, Phase II [early]; A.D. 550–650) in the Basin of Mexico was dominated by the state centered at Teotihuacan, with its influence extending throughout much of Mesoamerica during the century examined in this study. As is well known, the emergence of this state (during the First Intermediate, Phase IV; 100 B.C.–A.D. 100) coincided with much of the basin population residing at the center of Teotihuacan itself (Sanders et al. 1979:105–106). The period of occupation presently focused upon dates to several centuries after Teotihuacan's rise to preeminence, and was characterized within the Basin of Mexico by a resurgence of settlement outside of the great center (Sanders et al. 1979:110–111). The southern basin contained a relatively uniform scatter of small sites during this period, spatially interspersed with three centers. Our transformed map suggests the presence of three settlement clusters associated with these centers: in

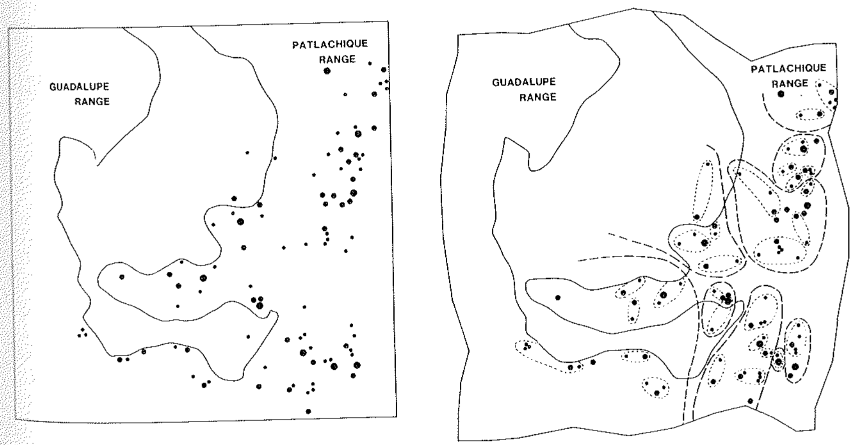

FIG. 6. Terminal Formative settlement, in geographic space and travel time space, in the southern Basin of Mexico. Left, original; right transformed.

the eastern and northeastern portion of the study area (encompassing several environmental zones east and southeast of Lake Texcoco), in the southwestern portion of the study area (on the western portion of the Ixtapalapa Peninsula and southern shore of Lake Xochimilco, predominantly in the alluvium, and lower and middle piedmont), and in the southeastern portion of the study region (east of Lakes Texcoco and Chalco, encompassing predominantly alluvium, and lower and middle piedmont; Fig. 7).

The fourth phase of occupation examined in the present study is the Early Toltec period (Second Intermediate, Phase I; A.D. 750–950). Population in the entire Basin of Mexico declined during the Early Toltec occupation, the total being only two-thirds that of the preceding period (Sanders et al. 1979:129). In contrast, population in the southern basin *increased*—probably a reaction to the fall of Teotihuacan at the end of the Classic period, and the subsequent reduction in its regional domination as an administrative and population center. A three-level settlement hierarchy continued in our study area, with previous researchers defining four clusters of settlement in geographic space: in the northeastern portion of the study area (the northern Texcoco region, extending further north into the Teotihuacan region), in the east-central portion of the study area (the southern Texcoco region), in the south central portion of the study area (throughout most of the Ixtapalapa region), and in the southeastern portion of the study area (the Chalco region, from Lake Chalco eastward; Sanders et al. 1979:130–132). The transformed map of Early Toltec settlement, in turn, suggests the presence of six clusters of settlement in the region of interest: two in the northeastern portion of the study area (the northern Texcoco region, one oriented toward the alluvium and lower piedmont, one toward the lower and middle piedmont), one in the eastern portion of the study area (the alluvium, and lower and middle piedmont east of Lake Texcoco), one in the central portion of the study area (mainly the alluvium and lower piedmont of the eastern Ixtapalapa Peninsula), one in the southwestern portion of the study area (predominantly the alluvium and lower piedmont of the western Ixtapalapa Peninsula and southern shore of Lake Xochimilco), and one in the southeastern portion of the study area (encompassing several environmental zones southeast of Lake Chalco; Fig. 8).

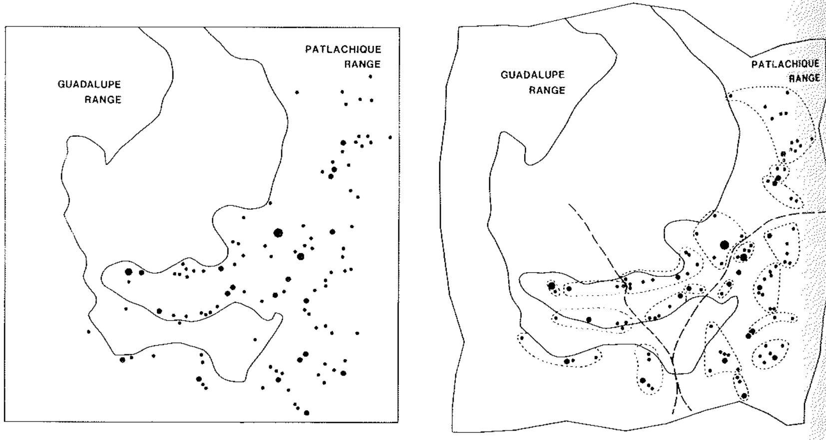

FIG. 7. Classic settlement, in geographic space and travel time space, in the southern Basin of Mexico. Left, original; right, transformed.

Finally, we examine settlement patterns in the southern Basin of Mexico during the Late Toltec (Second Intermediate, Phase II; A.D. 950–1150) period of occupation. Despite an increase in the number of sites present in the Basin of Mexico during this period, due to a shift from larger to smaller settlements total population continued to decline (Sanders et al. 1979:139–140). This decrease in population was particularly marked in the southern basin. Three tiers of regional administration continued in the study area, with the political domination of the entire basin probably centered beyond its bounds at Tula (northwest of the basin) and Cholula (southeast of the basin; Sanders et al. 1979:149). The transformed map of settlement for this period suggests the presence of two large settlement clusters oriented around centers: one in the eastern portion of the study area (encompassing several environmental zones east of Lake Texcoco) and one in the southern and southeastern portion of the study area (encompassing several environmental zones on the Ixtapalapa Peninsula, south of Lake Xochimilco, and east of Lake Chalco; Fig. 9).

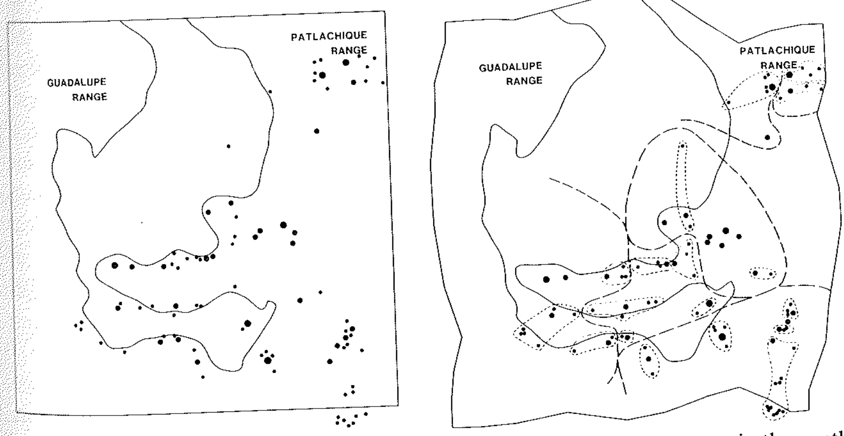

FIG. 8. Early Toltec settlement, in geographic space and travel time space, in the southern Basin of Mexico. Left, original; right, transformed.

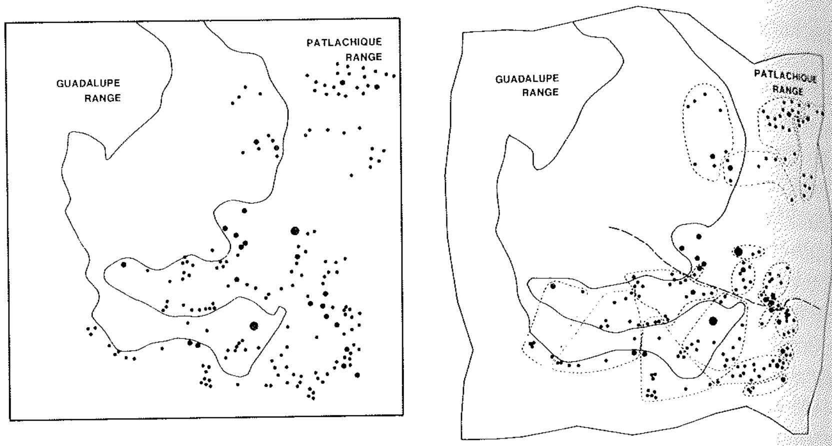

FIG. 9. Late Toltec settlement, in geographic space and travel time space, in the southern Basin of Mexico. Left, original; right, transformed.

One principle that can be explored with these proposed patterns of settlement interaction concerns the role of information processing in the development of regional administrative hierarchies. The roots of this line of inquiry lie in management science and the sociology of organizations (e.g., Simon 1962, 1973; Blau 1968; Blau and Schoenherr 1971; Cummings et al. 1974). However, it has been proposed in a number of anthropological contexts as a means of understanding both the evolution of small group decision-making behavior (Johnson 1983; see also Johnson 1978, 1982; Reynolds 1984), and the emergence of settlement hierarchies in complex societies (Wright 1969:3–6; Johnson 1973:1–4; Wright and Johnson 1975:285; Flannery and Marcus 1976). The essence of this concept lies in Ashby's principle of *requisite variety* (Ashby 1956); in the context of information processing, it states that an increase in the number of information sources within an integrated system ultimately will lead either to the collapse of the system or to the emergence of an administrative hierarchy to meet growing information processing requirements (Johnson 1978). Through focusing upon this general concept, one indirectly considers many of the proposed "prime movers" of sociopolitical development—such as population pressure and the implementation of hydraulic agriculture (cf. Wright 1977)—whose impacts may be considered in terms of additional types of information in a system and associated increases in the need to process this information.

In our transformed maps and the spatial aggregations based upon them, support for the above information processing construct would occur as regular patterns of spatial affiliation, or geographic spans of control (cf. Johnson 1982:411). A visual inspection of the maps does not provide such support, for the aggregations vary greatly both in size and in the nature of their components. But the proposition of interest also can be assessed in terms more directly related to information processing itself. The following graphs enable such an evaluation—measuring the information processing tendencies suggested by proposed aggregations of sites both in terms of the number of *settlements* associated with a particular administrative site and in terms of the number of *people* associated with a particular administrative site (Figs. 10 through 14). The latter helps to incorporate variability in the sizes of information sources, thus allowing for the possibility that sites containing different numbers of people generate different amounts of information to be processed. The former, as discussed further below, helps to eliminate possible differences in the sizes of units ultimately providing information—an important potential source of variability.

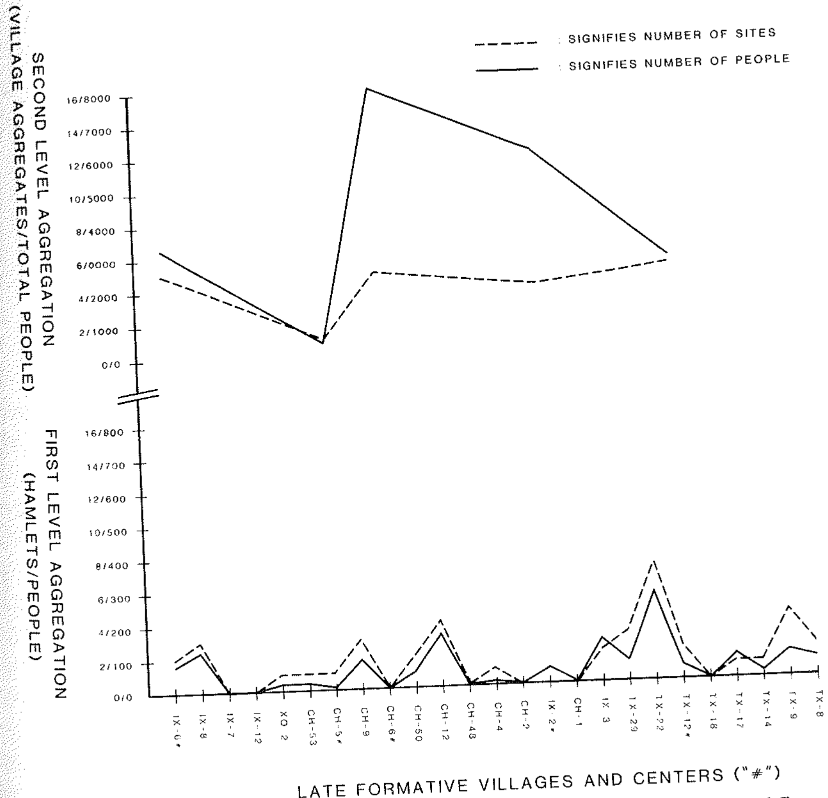

FIG. 10. Graph of Late Formative information processing, based upon proposed first and second level settlement aggregations presented in Fig. 5.

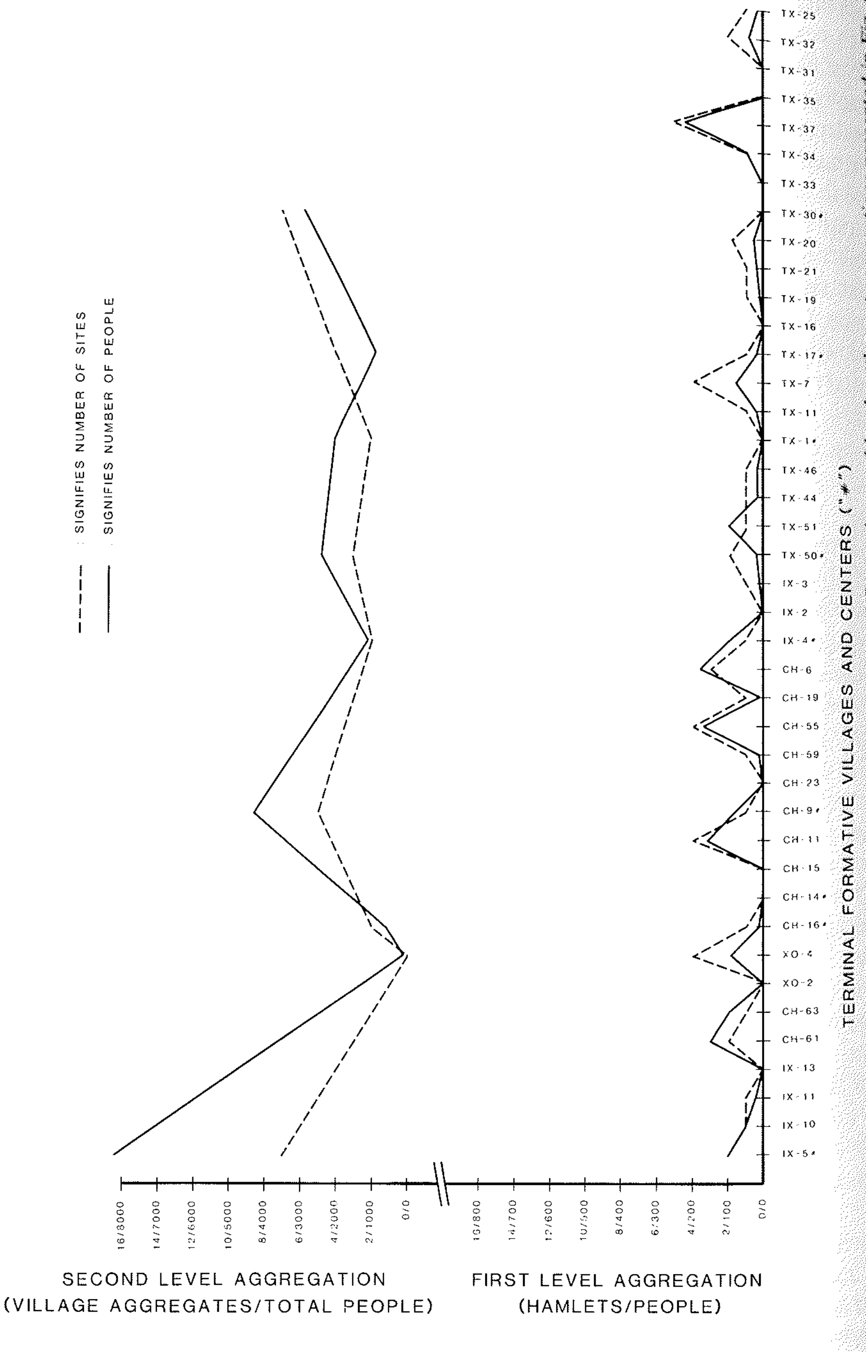

FIG. 11. Graph of Terminal Formative information processing, based upon proposed first and second level settlement aggregations presented in Fig. 6.

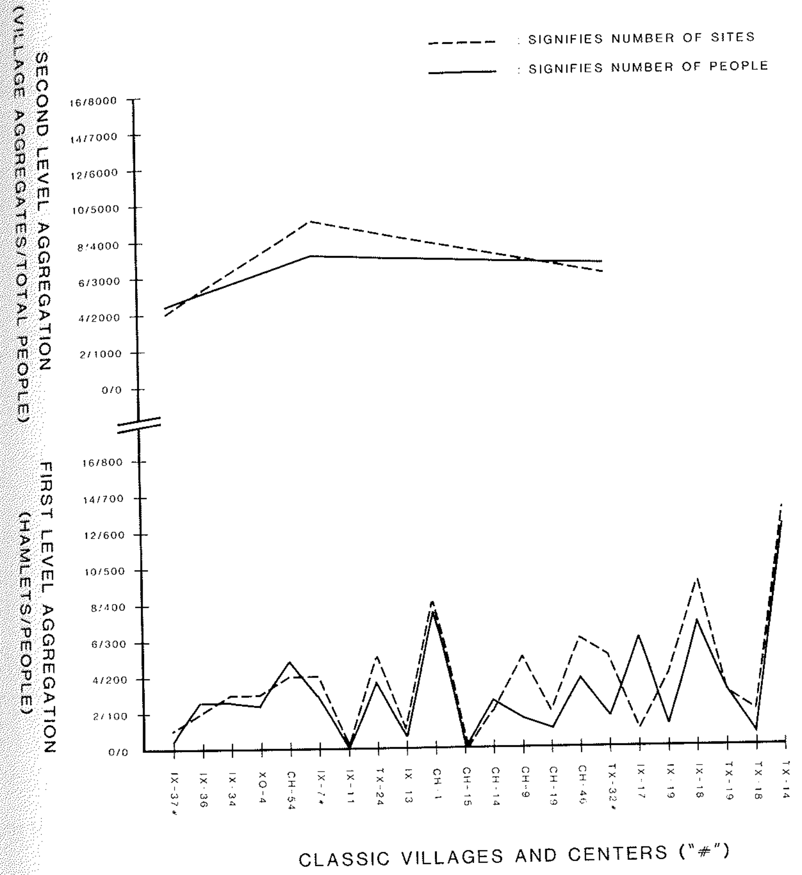

FIG. 12. Graph of Classic information processing, based upon proposed first and second level settlement aggregations presented in Fig. 7.

A formal comparison of the graphed patterns suggests a degree of regularity in information processing. By first calculating the means and variances of the proposed information processing tendencies at each level of aggregation (Table 2), and then comparing the means statistically, differences among information processing patterns can be assessed for the various periods of occupation. For the first level aggregation, a null hypothesis of equal means cannot be rejected in 40% of the comparisons (at a .05 level of significance) for either individuals or hamlets; for the second level aggregation, the same hypothesis cannot be rejected in 70% of the cases for individuals or village aggregates (Table 3). Given that the rejection of this hypothesis in essence signifies irregularity in information processing tendencies, notice that for both levels of aggregation the rejection

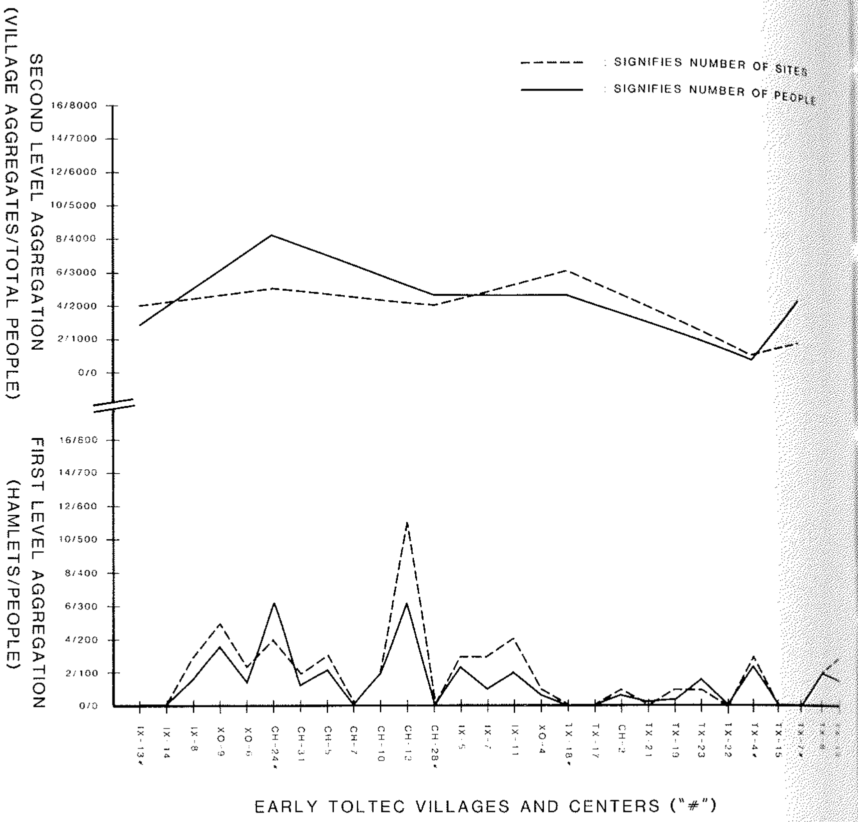

FIG. 13. Graph of Early Toltec information processing, based upon proposed first and second level settlement aggregations presented in Fig. 8.

of equal means *always* involves either the Classic or Late Toltec periods. Both were periods of occupation where *supraregional centers* are thought to have wielded a great deal of influence over the Basin of Mexico. Their range of influence quite likely included patterns of information processing and decision making.

In terms of the data on proposed information processing patterns summarized in Table 2, spans of control on average encompassed fewer sites and people during time periods which lacked a supraregional center. One possible explanation for this is that the supraregional centers present in central Mexico during the Classic and Late Toltec periods somehow modified local information processing and decision-making patterns, perhaps replacing their own administrative representatives throughout the region to control disproportionately large amounts of local decision making (as occurred in the northeastern basin during the Late Horizon period; cf. Evans 1980:103–111). The three periods for which similarities in information processing occur all most likely involved chiefdoms, with the Late Formative and Terminal Formative systems evolving toward greater levels of sociocultural complexity, and the Early Toltec period representing a regional decline following the demise of Teotihuacan.

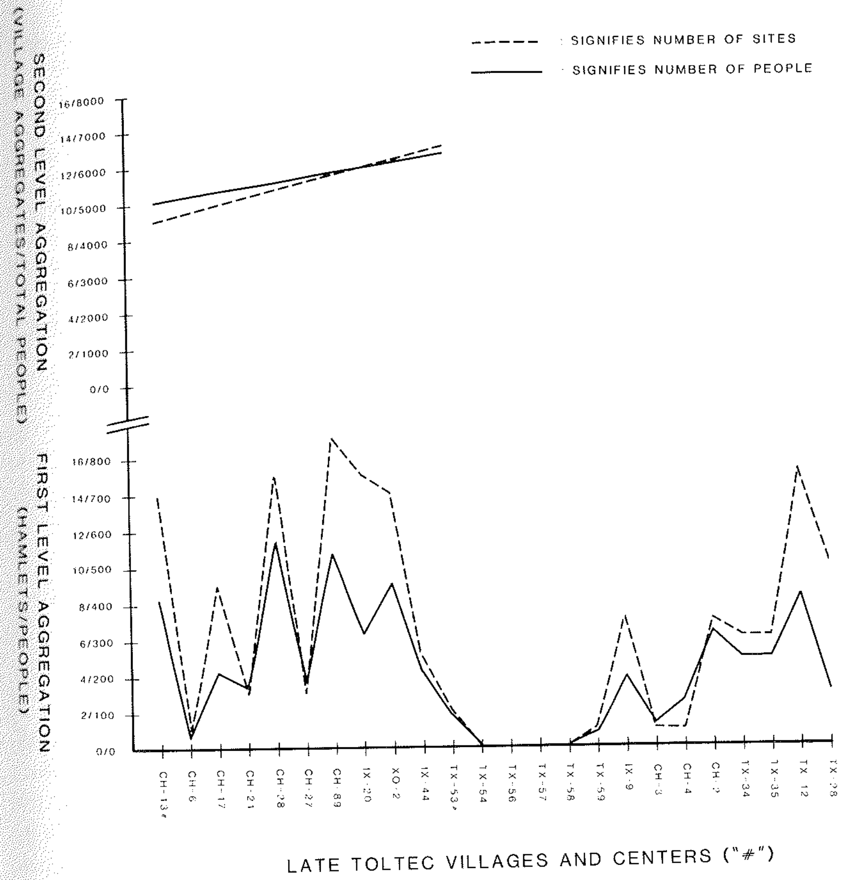

FIG. 14. Graph of Late Toltec information processing, based upon proposed first and second level settlement aggregations presented in Fig. 9.

Until now, the evaluation of regional patterns of information processing has searched for certain regularities. An alternative perspective approaches the problem in terms of *irregularities*, or violations of the principles underlying the information processing theme. In the present research setting, we cannot propose precisely when a particular administrative level will appear. An information processing *threshold*, if it exists,

TABLE 2

Means and Variances of Proposed Information Processing Patterns for the Late Formative through Late Toltec Periods in the Southern Basin of Mexico

	First Level Aggregation				
	Hamlets		People		
	Mean	Variance	Mean	Variance	N
Late Formative	1.6	1.7	53.2	64.5	25
Terminal Formative	1.3	1.3	47.9	59.9	41
Classic	3.8	3.1	139.2	144.0	22
Early Toltec	1.9	2.3	69.0	84.5	28
Late Toltec	6.3	5.9	204.6	171.2	24
	Second Level Aggregation				
	Village aggregates		People		
	Mean	Variance	Mean	Variance	N
Late Formative	4.0	1.7	4032.0	2935.9	5
Terminal Formative	3.6	2.4	2503.3	2524.9	9
Classic	6.3	2.5	2972.7	799.9	3
Early Toltec	3.7	1.9	2124.7	1299.4	6
Late Toltec	4.0	2.8	5360.0	919.2	2

would generate a higher order settlement at that threshold level *and* at all levels beyond it—presumably until another threshold is reached, producing a subsequent hierarchical response. But we can further evaluate the information processing hypothesis by noting the presence of certain irregularities, namely the presence of higher-order administrative settlements in situations which also generate either lower-order administrative settlements or none at all.

Violations could take the form of villages without interacting hamlets, or centers either without interacting settlements or under proposed information processing conditions which also give rise to lower-order administrative settlements. As indicated in Figs. 10 through 14, such irregularities do occur, in different frequencies, for all time periods examined. Violations are particularly evident in the first level aggregations where villages arise in the absence of interacting hamlets. Interestingly, this occurs only twice (9.1% of the cases) during the Classic period and four times (16.7%) during the Late Toltec period—the periods in which information processing regularities are not supported statistically. Greater frequencies of violations are evident during periods when the proposition is supported—the Late Formative, Terminal Formative, and Early Toltec periods (7 [28.0%], 12 [29.3%], and 9 [32.1%] instances, respectively)—again preserving the distinction between two periods where a supra-regional center dominated the basin and the three remaining periods examined. Although obvious violations among second level aggregations are less evident, small clusters of village aggregates during the Late Formative, Terminal Formative, and Early Toltec periods suggest irregularities.

TABLE 3

t Statistic Values for Testing Differences between Means of Information Processing Patterns

	LF	TF	CL	ET	LT
(a) First level aggregation: Hamlets					
LF	—	—	—	—	—
TF	0.9*	—	—	—	—
CL	−2.8	−3.6	—	—	—
ET	−0.5*	−1.3*	2.9	—	—
LT	−3.7	2.3	−1.9*	−3.4	—
(b) First level aggregation: People					
LF	—	—	—	—	—
TF	0.3*	—	—	—	—
CL	−2.6	−2.8	—	—	—
ET	−0.4*	−1.1*	2.0	—	—
LT	−4.1	4.3	−1.4*	3.5	—
(c) Second level aggregation: Village aggregates					
LF	—	—	—	—	—
TF	0.4*	—	—	—	—
CL	1.4*	1.7*	—	—	—
ET	0.3*	1.0*	1.6*	—	—
LT	3.3	3.4	1.9*	3.4	—
(d) Second level aggregation: Total people					
LF	—	—	—	—	—
TF	0.9*	—	—	—	—
CL	0.7*	−0.5*	—	—	—
ET	1.3*	0.4*	1.2*	—	—
LT	−1.1*	−2.9	−3.3	−4.2	—

Note: "*" signifies periods with no significant differences between means, $p = .05$.

As a final note on analytical results, in the search for greater consistency in patterns of settlement interaction we also employed a basic gravity model. This represents an attempt to account for the impact of settlement size as a key factor in determining patterns of spatial interaction. The measure of separation between places was determined from the transformed travel time maps—thus incorporating the notion of functional accessibility central to this study. Specifics aside, none of the gravity model applications produced appreciable changes in the regularity of settlement interaction and information processing patterns.

In summary, the above analysis suggests that similarities in regional information processing characterized three of the five periods of occupation examined in this study. Explanations consistent with our knowledge of basin prehistory have been offered to account for the two periods where the information processing hypothesis was rejected statistically. And yet support for this principle is hardly overwhelming, for the statistical regularities emerge admist individual violations and general variability. Before closing, we take a moment to discuss possible origins of this variability. Many of the possible sources of variability concern the assumptions which of necessity must underlie such a study; it is instructive to consider the indications of regularity in information processing in light of these possible complicating factors.

Difficulties inherent in employing archaeological data for such a study present an obvious source of potential variability. Despite the quality of the settlement data employed, it is always conceivable that some sites were missed and thus not included in the proposed spatial aggregations.[6] Moreover, in the absence of additional information we have assumed that all settlements present during a particular archaeological period were contemporaneous and could have interacted and exchanged information. This assumption may be incorrect, especially for a long time period such as the Late Formative. Indeed, the tendency for hamlets located close to other hamlets in geographic space to bunch tightly together in travel time space may indicate successive relocations of a small site—an adaptive response to situations such as soil depletion with limited penalties to small sites in terms of lost investments in infrastructure. As a final consideration related to settlement data limitations, a certain amount of variability may be introduced due to an "edge effect." This refers in particular to the northeastern and southwestern boundaries of the study area, and the possible exclusion of sites outside of these boundaries which were administratively linked to sites within. Such effects probably are minimal on the northeastern boundary, which is delimited by the Patlachique mountain range, though settlement clusters continue northward beyond the study area during the Early Toltec period. The southwestern boundary is a different matter, for it was defined largely by the edge of the Mexico City urban sprawl at the time the archaeological surveys were conducted.

A second possible source of variability concerns the possibility that settlements do not always affiliate administratively with the places most accessible to them. It is important to note that such behavior would introduce considerable spatial inefficiency. Although this is not considered by researchers exploring information processing in group decision making, such inefficiency in part challenges the information processing principle by virtue of providing regional systems which can exist despite excessive information processing costs. Detailed studies of northeastern Basin of Mexico settlement during the Late Horizon in fact do indicate some regional inefficiency—particularly in terms of energy extraction but also in terms of information exchange (Gorenflo and Gale 1986; Bell et al. 1988; Gorenflo 1990). Our understanding of the spatial inefficiency which can be incorporated within successful regional systems remains very limited. With particular regard to the present study, the information processing costs associated with inefficient regional organization are a problem demanding further attention.

A third and possibly most important source of variability in the above study concerns human information processing itself. Considerations underlying information processing capabilities of individuals frequently provide the foundation for models of emerging hierarchies in organizations (e.g., Simon 1971:202–208, 1973, 1976; Mahew and Levinger 1976; Johnson 1983:392–393). One of the most crucial concerns the possibility that different problem solving tasks require different types and amounts of information (Wright 1969). This has been suggested as a reason accounting for the presence of varying numbers of information sources in modern decision-making structures (Johnson 1982:412)—with "simple" tasks enabling the incorporation of more information sources than "difficult" tasks. Of a related nature is the degree to which the level of effort required to process similar types of information can differ. Such varying administrative intensity has been proposed to account for broad variability in information processing among settlements in Late Imperial China, where the additional effort required to administer settlements on regional peripheries led to the development of smaller administrative units in those areas (Skinner 1977:321). Due to the absence of specific data on the administrative challenges faced by each of the settlements considered in our study, we were forced to treat information exchange in the southern Basin of Mexico as a uniform process—similar types of information processed at similar levels of intensity. However, such considerations do help to explain both statistical variability and individual violations in proposed information patterns. In the case of statistical variability, it is worth noting that the settlement clusters proposed for the Classic and Late Toltec periods incorporate broader areas and larger numbers of ecological zones at both the first and (especially) second levels of aggregation. The need to incorporate varying economic activities generated from these increased ecological spans of control may well have led to different information processing mechanisms at the level of both villages and centers. One possibility would be the processing of less information, or fewer types of information, from a larger number of sites and economic activities; this of course may have been modified further by the influence of supraregional centers, as previously discussed. In the case of individual violations of expected information processing principles, the presence of administrative settlements in the absence of subservient settlements was consistently the greatest during periods where larger numbers of separate centers existed—introducing the possibility that greater numbers of individual polities may have required increasingly intensive administration in particular cases. Along the same line of reasoning, the periods with fewer violations were those where the Basin of Mexico ultimately was ruled by a supraregional center, and thus when competition between separate polities would likely have been controlled much more closely.

Another possible source of variability associated with information processing concerns the numerous strategies employed by humans to organize information processing units and make decisions. Two considerations, both exceedingly difficult to deal with archaeologically, deserve mention: variability in the size of basal units, and the possible use of decision-making heuristics. Basal units represent the basic components of an information processing organization which contribute information to the next level in a decision-making hierarchy. As basal units themselves become larger and process more information internally, the information processing requirements of the next level of the hierarchy are reduced (Johnson 1982:398ff). For the present study, we have assumed that basal units were constant across time periods, once again in lieu of information to the contrary. In particular, variability in basal unit size could affect information processing patterns when assessed based upon numbers of individual persons, for basal units may in fact comprise nuclear families, extended families, or some other social unit. Such considerations should cause less difficulty when settlements (hamlets or village aggregates) are considered as basal units, since variability of smaller social units would be encompassed within these larger collections of people.

Heuristics frequently are employed by humans when dealing with large amounts of information (cf. Kahneman et al. 1982). Although there is a recognized need to treat human organizations as cognitive systems (e.g., Ramos 1981:44ff), studies of cognitive processes such as heuristic decision making in organizational contexts have lagged behind. As is the case with individual decision makers, varying reductions in the amounts or types of information considered, or intensity of its consideration, are quite possible. The message which comes through here is that human information processing and decision making at both the individual and group levels in many ways appear to be inherently variable. Where decision-making heuristics are concerned, uniformity may indeed be the exception rather than the rule.

CONCLUDING REMARKS

The realization that human spatial behavior may be described and analyzed more accurately through the use of alternative spaces was an important discovery in human geography. Recent theoretical and technical advances in geographical research enable the definition and exploration of such spaces, opening several new avenues of inquiry on human spatial organization. In terms of basic spatial problems, archaeological data are no different from most data on modern human behavior: evidence in both research settings occurs in geographic space, but understanding its arrangement may require exploring alternative representations of this space.

The above essay was written with three primary goals in mind. First, we wanted to introduce archaeologists to the concept of relative spaces, and to the insights on regional organization that can emerge from the examination of these spaces. Second, we wanted to introduce archaeologists to a particularly useful method for developing maps of different spaces. Finally, we hoped to demonstrate how these ideas might be applied to develop a representation of travel time space—and, in turn, how the arrangement of settlements in such a space provides a means of evaluating the proposition that political hierarchies evolved in response to increasing information processing requirements.

Regularities in the proposed spatial–hierarchical relations between settlements in the southern Basin of Mexico were found in the Late Formative, Terminal Formative, and Early Toltec periods of occupation, supporting the information processing hypothesis. This support emerged amidst considerable variability, and several possible sources were discussed. Some concern possible weaknesses in the data employed, notably questions of settlement contemporeneity and the possibility that the regional and administrative functions of all settlements might not have been discovered or interpreted properly. A second potential source of variability concerns the possibility that patterns of settlement affiliation were not always based upon spatial accessibility. The final possible source of variability discussed concerns aspects of human information processing in general, in particular differing types and intensities of information processing, shifts in the sizes of basal units of information processing, and the inherent variability in human information processing and decision making which can be subsumed under the general heading of heuristics. The information processing hypothesis was not supported by settlement data from the Classic and Late Toltec occupations of the southern Basin of Mexico. However, the presence of supraregional centers in central Mexico during both of these periods may account for this lack of support—with overriding administrative concerns of major political powers affecting regional organization in a manner similar to that which occurred in the basin during the Late Horizon.

APPENDIX I

Denoting the travel time between points *i* and *j* as d_{ij}, and the Euclidian distance between the same points as d_{ij}^*, the trilateration algorithm may be outlined as the following steps.

Step 1. Generate an initial configuration of the *n* points of interest (Fig. 15a). In general, this configuration may be arbitrary; in the present study, we employed the original locations of the 25 sample points.

Step 2. Connect each point to all others with straight lines which pass through every pair of points (Fig. 15b).

Step 3. On each line, for which a distance has been calculated, center a line segment of length d_{ij} (Fig. 15c).

Step 4. Draw vectors ds_{ij} from each point to the end of the line segment (Fig. 15d).

Step 5. Find the resultant vector, representing the average of all vectors (Fig. 15e).

Step 6. Move each point *p* to a new position *p'*, defined by the endpoint of the resultant vector.

Step 7. If no points have moved significantly, according to some predefined criterion, stop; if points have moved, then return to Step 2 and continue iteration.

The lengths of the vectors from each point are calculated by

$$ds_{ij} = (d_{ij} - d_{ij}^*) / 2.$$

The direction cosine of each vector is found by

$$\cos \theta_{ij} = (x_i - x_j) / d_{ij}^*.$$

From the above two equations, change in the *x* direction is computed as

$$d(x)_{ij} = \cos \theta_{ij}\, ds_{ij}.$$

Similarly, with respect to change in the *y* direction the following equations are employed:

$$\sin \theta_{ij} = (y_i - y_j) / d_{ij}^*$$

and

$$d(y)_{ij} = \sin \theta_{ij}\, ds_{ij}.$$

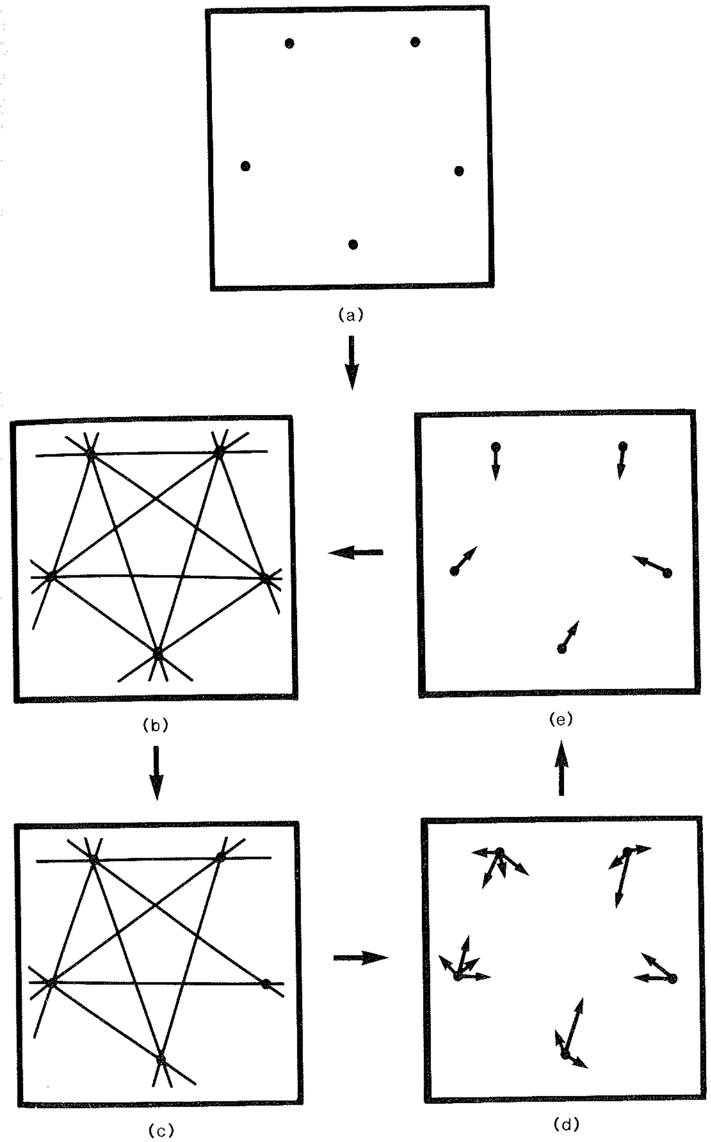

FIG. 15. Graphic depiction of the trilateration procedure.

The average vector represents the mean change in both the *x* and *y* directions. These are computed, respectively, as

$$d(x)_i = [1/(n - 1)] \sum_{j=1}^{n} d(x)_{ij}$$

and

$$d(y)_i = [1/(n - 1)] \sum_{j=1}^{n} d(y)_{ij}.$$

Thus the point p, defined by (x_i, y_j), is moved to the new point p', defined by $(x_i + d(x)_i, y_i + d(y)_i)$.

ACKNOWLEDGMENTS

This study was made possible largely through the work of Professor Waldo Tobler, both in pioneering many of the concepts drawn upon and in generously providing us access to his computer cartographic software. Sally Boyle, Sara Burt, Tacy Costanzo, Richard Hearne, and David Lawson assisted in producing various figures. An earlier version of this paper was commented upon by Peter Gould; further comments were provided by two particularly insightful anonymous reviewers. Remaining omissions or misinterpretations remain our own.

NOTES

[1] Prehispanic settlement data have been collected from the entire Basin of Mexico, as documented in Sanders et al. (1979). However, a final compilation of data from the northeastern (Temascalapa and Teotihuacan regions) and western (Cuautitlan region) portions of the basin for all periods has yet to be undertaken. As the nature of this study requires data from contiguous areas, we have been forced to focus upon the southern basin.

[2] Plog's examination of settlement location in Formative Oaxaca, where the spatial proximities of sites were defined in terms of similarities of ceramic design elements, employed such ideas in an archaeological context (Plog 1976:268–270). In a more complex example, Tobler and Wineburg attempted to predict the locations of pre-Hittite settlements in Bronze Age Anatolia through measuring spatial proximities in terms of how frequently settlements were mentioned in the same cuneiform tablets (Tobler and Wineburg 1971).

[3] Although relatively slow, canoe travel nevertheless played a key role in Basin of Mexico regional organization—providing a means of transporting bulk materials (such as maize) which was as much as 40 times more energetically efficient than transporting such materials by foot (Hassig 1985:134). A study of the "energetic space" of the basin would shrink its center relative to the periphery, depicting the energetic benefits of movement on the central lake system.

[4] We begin this study with the Late Formative period because it provides the first evidence of a three-tiered settlement hierarchy in the Basin of Mexico, as discussed later in the essay. We do not consider periods of occupation beyond the Late Toltec because unique administrative problems during the succeeding Aztec occupation tended to override locationally based patterns of settlement affiliation. In the Early Aztec period, these problems revolved around intense competition between the separate city states which then dominated the basin (Gibson 1964:20–21). Adaptation to this competition almost certainly involved spatial responses, such as the arrangement of settlement for purposes of protection. During the Late Aztec period, the need to control previously autonomous city states led leaders of the Triple Alliance—the ruling body of the Basin of Mexico—to force these polities to interweave their spatial-administrative hinterlands (cf. Evans 1980:103–111; Evans and Gould 1982:287–288; Hodge 1984:25–26). Thus we know that spatial proximity among Late Aztec sites was not indicative of administrative affiliation.

[5] The distinction between provincial and regional centers rests mainly upon the administrative presence of even larger sites. Provincial centers originally were defined as large nucleated communities with ceremonial architecture dating to a period when the basin *was* dominated by a supraregional center. Regional centers, in turn, originally were defined as large nucleated communities with ceremonial architecture dating to a period when the basin *was not* dominated by a supraregional center (Sanders et al. 1979:55–56).

[6] In the Texcoco region, composing much of the eastern section of our study area, some sites may have been missed in two narrow strips not examined completely (cf. Parsons 1971:17–19). However, most of the larger southern strip was surveyed systematically, though not on a field-by-field basis. Moreover, daily trips for a period of several months along the highway which runs the length of the northern strip enabled its examination for the presence of sites with mounds. As a result, a number of sites were recorded within both strips, and according to the director of the Texcoco survey it is unlikely that any medium or large sites in these two areas were missed (Parsons 1971:19).

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Group Size and Societal Complexity: Thresholds in the Long-Term Memory

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This paper attempts to establish the empirical generalization that there are panhuman thresholds that regulate man's organization of his natural and social environment. The thresholds are, it is proposed, related to underlying regularities in the organization of the long-term memory. Based on the proposed constraints, the paper also suggests some hypotheses concerning group size and hierarchical complexity. © 1990 Academic Press, Inc.

One universal on which anthropologists agree is that all cultures use classification to reduce and order the phenomenal world. Recently, ethnobiologists (Berlin et al. 1973; Berlin 1976; Brown et al. 1976; and others) have suggested that beyond the mere fact of classification there are also cross-cultural regularities in the way different cultures classify the natural environment. One of these cross-cultural regularities seems to be the existence of numerical thresholds in ethnobiological classifications.

It is suggested in this paper that the same thresholds are also present in the ordering of man's social environment. It is argued that these thresholds are panhuman and reflect regularities in the organization of the long-term memory. The constraints that limit group size have, it is further argued, general structural implications for the formation of hierarchies and thus social complexity.

The proposition that a new level of integration will appear "after some critical threshold in need for information-processing is reached" was first suggested by Flannery (1972a:423) and since then elaborated into a theory for the development of societal complexity by Wright (1977) and Johnson (1978; Wright and Johnson 1975). This paper follows the approach used in Johnson's later works (1982, 1983) and instead of relating the thresholds to the total information-processing needs of a society, the thresholds are derived from the information-processing limitations of the individual. The specific hypothesis in this paper is that a new level of integration will appear when the size of the top decision-making unit exceeds a critical

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