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THE QUANTITATIVE MODELLING OF HUMAN SPATIAL HABITABILITY

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Professor Michael Benedikt, who first developed isovists for architectural analysis and who offered his insights and experiences at the inception of this study.

"There are no rules of Architecture for a castle in the clouds"

G. K. Chesterton

(Castles <u>above</u> the clouds, however, are a different matter, entirely.)

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SUMMARY

This study presents a model for the quantitative assessment of human spatial habitability in the space station context. Its conceptual basis for this is graphically represented in the structural diagram of figure i. This shows that spatial habitability is conceived in terms of three major aspects: VISUAL, KINESTHETIC AND SOCIAL LOGIC.

The Visual aspect assesses how interior spaces appear to their inhabitants. This aspect concerns criteria such as sensed spaciousnes and the affective (emotional) connotations of settings' appearances. The Kinesthetic aspect evaluates the available space in terms of its suitability to accommodate human movement patterns, as well as the postural and anthropometric changes due to microgravity. Finally, Social Logic concerns how the volume and geometry of available space either affirms or contravenes established social and organizational expectations for spatial arrangements. Here, the criteria include privacy, status, social power and proxemics (the uses of space as a medium of social communication). All of these aspects are functionally interconnected in the design of habitat, but for analysis, the model is organized so that each may be independently evaluated. That is, operationally distinct techniques and measures have been defined for each of these aspects so that it is possible to hold some levels of evaluation criteria constant while investigating design manipulations that vary others. Thus, it is possible to equalize hypothetical crew cabin arrangements in terms of spaciousness measures, and then to comparatively assess these cabins' performance in terms of some other criteria , such as accommodation to body motion envelopes.

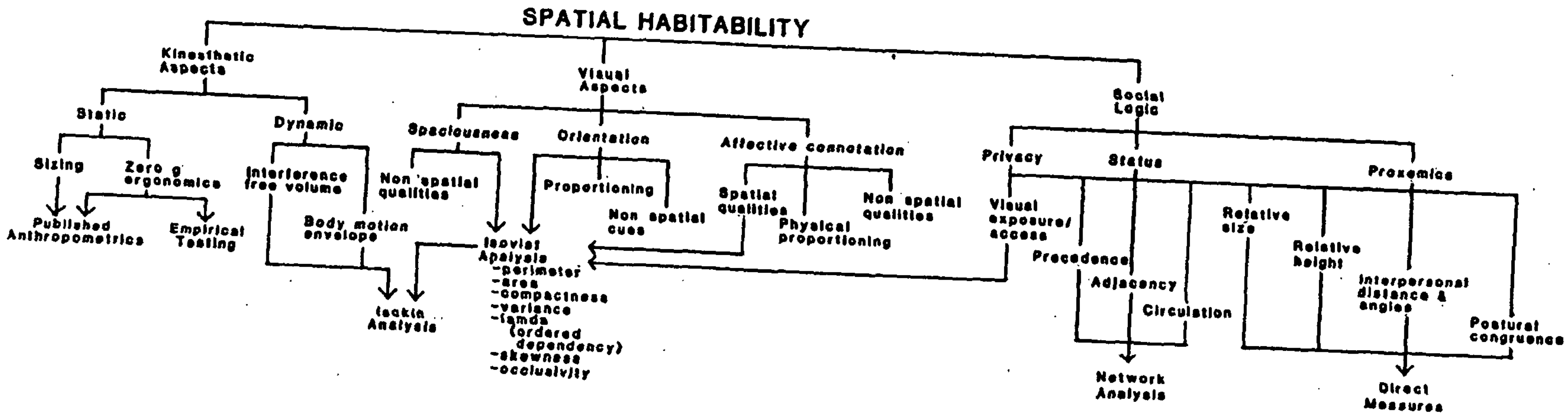


Figure i

The Structural Hierarchy of Spatial Habitability

The stuctural diagram shows that certain measures of one aspect of habitability are functionally (and formally) related to those of another. For example, visual privacy, a concern of Social Logic, is addressed in terms of visual access and exposure. But these quantities can be measured by the isovist model, which also is used to analyze spaciousness. A slight reworking of the isovist model then produces the Isokin model, which assesses available volume and body motions. The structure here involves a few powerful ideas that can be manifest in different ways to meet the functional demands of evaluation.

This general, quantitative model of spatial habitability is then both a conceptual sustaining net and a set of specific tools that operationalize the behavioral bases of spatial volume and geometry. It can be applied to any size or shape interior, at any scale of consideration, from the station as a whole to an individual enclosure or workstation.

An example of an application may be as follows: Given 'n' hypothetical private crew quarters of approximately equal sizes, which is the best design in terms of meeting spatial habitability criteria?

In terms of visual criteria, spaciousness is seen as a major goal. The larger a cabin appears, without being physically larger, the better the visual spatial habitability. The isovist model operationalizes this concern for spaciousness in terms of distributional measures on the space that is visible (the isovist) from selected vantage points. These points might include the sleep restraint and entry positions. Isovists are computed from these positions and various distributional measures are compared across cabins. Generally, the cabin with the highest area and variance and the lowest lambda measures from the greatest number of positions should appear most spacious. Area measures visible space available, variance is sensitive to long views, and lambda is a measure of sequential irregularity. Interior spaces are seen as more spacious to the degree that more space is visible, long (interior) view axes are available, and (in design terms) "the eye moves smoothly about the space." Our full study computes values of these measures that can be expected for various-shaped enclosures. Elongated forms of at least 150 ft^3 seem to perform very well. For maximum spaciousness, area and variance should be as large as possible, and lambda, minimal. If cabins show advantages in one or more measures and tradeoffs need to be made, we can say with some confidence that area appears to be most important, variance a close second, and lambda, a more distant third. But further simulation studies are needed to fully document the relative contributions of these measures of spaciousness.

Of course, the affective connotations--the emotional and attitudinal associations--that a space communicates are also important considerations. Rooms may be judged as "intimate," "boring," "secure" or whatever. Most of the studies that have investigated affective response to spaces show that these are mediated by nonspatial cues, such as light distribution, visual variety, type of furniture, availability of windows, etc. Some evidence exists that sloping ceilings are regarded as "friendly" and that extremely narrow (about 4:1 aspect ratio) spaces are felt to be "unpleasant." If we are <u>only</u> evaluating volume and geometry of crew cabins, the substantive data on affective connotations are very limited, but they do support giving a higher rank to a cabin with sloping or articulated "ceiling." Convergently, our study indicates that cabins should be designed with a ceiling because a "visual vertical" seems to aid orientation and an increased "height" dimension seems to enhance spaciousness. This latter effect would be reflected in an increased variance of the isovist taken through the saggital (R/L) plane.

The cabins also need to be evaluated in terms of their ability to accommodate body motions. Here, Isokin analysis is the requisite tool. Given a specified set of body motion envelopes, it places these within an enclosure and then calculates various measures of "goodness of fit." The goal here is twofold: to be able to accommodate, with least need for adaptation, the desired set of body motion envelopes in the greatest number of locations. A space where one is constrained to perform an action in only one location or in only one prescribed movement is less "habitable" than a space where one can do something via a variety of locations and movements. No overall evaluative judgments based on the shape of spaces alone is possible here. It is the <u>relation</u> of the form of the space to the form of the enclosed body motion envelopes that is critical. Isokin measures compute the interference-free area (which should be as large as possible), the percent of body motion envelope that needs adaptation, the amount and percent of radial interference (both of which should be as small as possible), and the "quality" of certain bumps that would occur when an inhabitant's envelope comes up against the enclosure (grazing angles should be low).

Cabins that show the most desirable levels of these variables have greater kinesthetic habitability. Our simulations strongly suggest that cabin volumes below 150 ft^3 would be unacceptable in terms of accommodating (without major constraining adaptation) even simple body motions associated with dressing needs. Cabins with a complex form--those that have both available elongated spatial and compact spatial components--appear to perform much better than simple or regular volumes. This is convenient, because visual spaciousness is enhanced in the same fashion. It implies that there need be no imposed tradeoffs between visual and kinesthetic spatial habitability. A "good" cabin design can spatially provide both.

Finally, the cabins need to be compared in terms of their conformity to the Social Logic of life in tight spaces. Here, again, there is a choice of criteria depending on the prevailing social and organizational climate. Is a space station crew organized in the manner of a military group or in terms of modern corporate "matrix management?' One has a highly imposed status hierarchy, the other expresses egalitarianism.

In the military model, a linear arrangement of cabins along a module axis would affirm a status hierarchy. If this cabin arrangement were utilized with an egalitarian model, there would be an imposed status gradient because surely one end of a module would be more desirable than another on the basis of availability to some resource (e.g, a window) or proximity to a nuisance (e.g, a hygiene station). A revolver-type arrangement of cabins around a cylindrical axis more effectively reflects an organization that strives to avoid interpersonal status concerns.

Social Logic may at times conflict with the functional requirements of other aspects of habitability. One immediate example is the tradeoff between visual area and visual privacy from a cabin doorway. Privacy is greater if a cabin door can be left open without exposing the entire interior to passersby. However, such a configuration inevitably decreases visual spaciousness from the entry position by occluding part of the interior space. The tradeoff here is resoundingly in favor of visual privacy, but other conflicts may not be so easily resolved.

Social Logic also requires that a sleep restraint (as the most personal place) be located furthest from the cabin door. There is a price here to be paid in terms of egress time in event of emergency. Whether this would be too costly depends on simulation study of the exact situation.

In this accumulative analytical fashion, it is possible to operationally assess many intangible aspects of spatial habitability. The <u>best</u> cabin design will be the one that "scores" highest on desired levels of most measures. If tradeoffs are necessary, there is a well-developed technology of multicriteria decision making available to aid their derivation. But this study suggests that such tradeoff decisions are unlikely to be needed. The options available to enhance spatial habitability are not limited ones, and imaginative design should be able to satisfy the various spatial habitability criteria to a high degree. Using this model's approach, spatial habitability becomes as amenable to careful measurement and assessment as do the traditional engineering concerns for remote habitats.

INTRODUCTION

This study explores the meaning and measurement of Human Spatial Habitability (HuSH). It addresses an old, but deceivingly simple-sounding question:

"How much physical space does a person need?"

Here, the addressed habitable volume refers to shirtsleeve crew quarters proposed for the first permanent U.S. space station scheduled for launch and construction in Earth orbit sometime in 1992.

At the time of this study, NASA is assembling relevant information on the development of volume and geometry design guidelines for the station's habitable modules. Along with such traditional engineering criteria as weight, strength, and efficient use of materials, there are also human concerns. NASA has committed itself to establishing a 90% productivity goal for crew operations, when compared to similar activities carried out earthside. Since the station will inevitably be a remote and confined setting, situated in a hazardous environment and dominated by machine functions, a high level of habitability will be required to ensure that all mission objectives can be met. This habitability requirement extends to considerations of crew organization, communications, work and rest schedules, food preparation, hygiene and ambient conditions of the interior. But the most basic questions involve the needed amount and configuration of habitable space itself. With every cubic centimeter of the station being part of the most valuable building in history, how much volume should be given over to meeting possible biological and psychological spatial needs of the crew?

As part of the attempt to generate human behavior and performance design guidelines relevant to volume and configuration, this research was undertaken as a nine-month project sponsored by the Space Human Factors Office at NASA-Ames Research Center. The purpose of the research was not to perform another confinement study, nor one that required human subjects' participation. Rather, the goal of this project was to quickly review the extant empirical studies, determine the state-of-the-art of habitability research, and then to develop a quantitative model of human spatial habitability. This model should be capable of measuring various aspects of spatial habitability, and it should be useable as a reference tool for actual design work.

This study is thus unlike earlier attempts to investigate habitability in confined environments. Where those sought empirical results, ours aims at a conceptual and quantitative framework that organizes extant knowledge in a manner which permits its application to a specific design problem. So it is not an exercise in experimentation but rather a process of validated, conceptual innovation.

The development process behind the models described here has actually followed a relatively straightforward path. First, extant literature was surveyed and summarized to create a state-of-the-art picture of how "spatial habitability" is currently conceived. This took the form of a base set of issues and concerns treated by the studies. These items were used in the development of a structural tree which permitted the preliminary organization of the aspects of spatial habitability as separate branches of the tree (see the following section). Each of these aspects were then operationalized to produce bottom line measures that, taken together, provide an overall assessment of spatial habitability.

In this process, research results that were not part of the original base set often became relevant as a way of validating the modelling approach. For example, the question of visual volume and its effects on perceived spaciousness arise repeatedly in the habitability literature (Davenport et al. 1963; Rosener et al. 1970; Dalton 1983; Parker 1985). This led us to adopt the ISOVIST model, as previously developed by Benedikt (1979) as a fundamental tool for measuring perceived space. The results we obtained in subsequent computer simulations suggested that there should be additional empirical evidence when human subjects are tested for judgments of interior volume. Where possible, we then located these other studies and confirmed our "postdictions" as a way of validating the utility of the isovist model.

The modelling results presented here are thus a product of a good deal of "experimental bootstrapping." When earlier investigators did not make use of the isovist formalism, we translated their manipulations of independent variables into isovist terms in order to compare them with more recent findings. Elsewhere, we developed new techniques to assess the substantive issues relevant to other aspects of spatial habitability.

This process of validating a model through "postdiction" from a pastiche of prior evidence is unfortunately highly dependent on the published record it utilizes. With regard to studies relevant to spatial habitability, this record is far from systematic. Prior investigators have chosen to study the effects of spatial manipulations from a variety of theoretical positions--most of which are incommensurate with each other. Many earlier studies also failed to control or to manipulate certain physical variables which our theoretical position deems as important. Thus, the experimental validation of several of our model's proposals is far from complete. Throughout this report, we have endeavored to emphasize those points that most urgently need more experimental verification.

At this time, the model presented here seems to be the most comprehensive of its kind in dealing with measurable qualities of the spatial environment and in linking those to established concerns of habitability. If it is correspondingly successful in aiding the imminent design decisions that must grapple with the requirements of human spatial habitability, this model will have fulfilled its guiding intentions.

HUMAN SPATIAL HABITABILITY: AN OVERVIEW

What Is Habitability?

The Habitability Research Group at NASA-Ames' Space Human Factors Office has defined 'habitability' as:

> ***A measure of the degree to which an environment promotes the productivity, well-being, and situationally desirable behavior of its occupants.***

This summarizes the traditional view that ". . . habitability requirements deal with safety, morale, psychological and physiological well-being, health, comfort and other human factors of the crew members. . ." (Davenport et al.

1963). It also recalls the earlier position of Fraser (1968), who saw "Habitability (as) that equilibrium state resulting from interactions among the components of the (hu)man-constructed environment complex . . . which permit (hu)mans to maintain physiological homeostasis, adequate performance, and acceptable social relationships." In short, habitability is about quality of life. It is, succinctly, a measure of the "fitness" of an environment for its inhabitants.

Experimental study and the modelling of habitability is undertaken for a variety of reasons (Righter et al. 1971):

(1) To predict human responses in prolonged exposure to a particular habitat.
(2) To identify specific problem cases which cause less than optimum habitability.
(3) To better understand the psychological and behavioral adjustment process to a habitat.
(4) To better understand individual variation in adjustment to a habitat.
(5) To provide general evaluative data on the assessable habitability of particular environments.

The end purpose of all of these is to generate better physical design guidelines, improved work schedules, information management systems and/or social organizations that enhance the fit between people and their settings. In this general sense, habitability in all its guises is a basic human concern of any environment, and according to Cohen and Rosenberg (1985), the issue of how much space crew members need is the most fundamental question of all.

What Is Spatial Habitability?

Spatial habitability refers to the ways in which the volume and geometry of livable space affect human performance, well-being and behavior.

Our review of the habitability literature and other studies on spatial perception and behavior has led us to organize the diverse considerations of spatial habitability into a structural hierarchy that aids their systematic investigation. This hierarchy was intermittently revised during the modelling process. As presented here, it represents a graphic summary of how this study has come to view spatial habitablity in the space station context.

Insert Figure 1

The hierarchy organizes Spatial Habitability into classes of three semi-distinct but complementary considerations. These are called its KINESTHETIC, VISUAL, and SOCIAL LOGIC aspects. They form the three main branches of the hierarchy. Each of these, in turn, decomposes into lower-order components based on a relation of inclusion. Items "further down" a branch are examples of how supraordinate items become operationalized. Items "further up" a branch are the reasons why we distinguish and measure the lower-order elements. The bottom line entries of the hierarchy describe

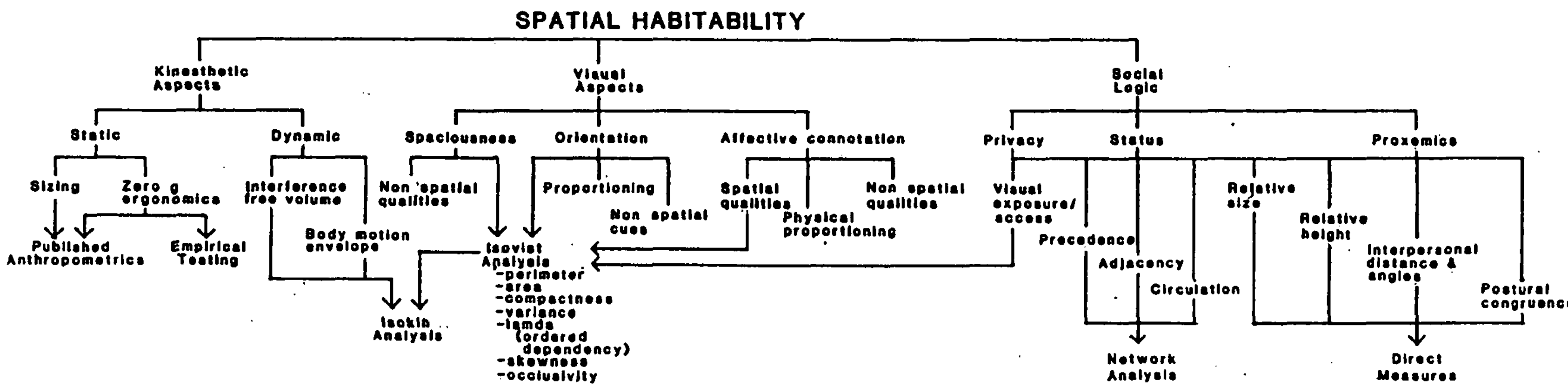


Figure 1

The Structural Hierarchy of Spatial Habitability final operationalized measures of each particular branch, as we currently conceive that aspect of habitability. Taken further, these measures provide the basis of an overall assessment scheme for any particular setting. Each branch of the structure is explored in detail within its corresponding section of this report. These sections include definitions and explanations of the entries, and the modelling results obtained from analysis by means of the bottom-line measures.

Human Spatial Habitability: The State-Of-The Art

With the advent of the U.S. manned space program in the early sixties, habitability research began in earnest to probe the questions of what makes confined and adverse environments livable. Three directions of study evolved out of these efforts.

First was the investigation of analogous settings; all of which share features of limited space, some degree of isolation and separation from others, and potential for exposure to a hazardous outside environment. Analogous environments include prisons, off-shore oil platforms, super-tankers, (ant)arctic research stations, submarines and deep-sea submersibles, underwater habitats, underground installations and even "capsule hotels."

Second was the simulation of missions through actual prolonged confinement of subjects in a laboratory setting or through analysis of simulated procedures and tasks. This is an experimental and/or modelling approach.

Third was the evaluation of historical precedents in both the U.S. and Soviet manned space programs. Actual experience on missions establishes what may be the most realistic data base yet for discovering problems of spacecraft habitability and for making ameliorative interventions. The SKYLAB missions in particular provided a wealth of information (Skylab 1975; Cooper 1976; Compton and Benson 1983; Pogue 1985) that is still being mined (Douglas 1984; Cohen and Rosenberg 1985). Recently, translations of Soviet experiences have also become available (Bluth 1984;1981;1979; Boeing 1983a).

There are several texts that thoroughly review the voluminous literature encompassed by the different approaches to habitability (Rasmussen 1973; Boeing 1983b; Stuster 1984; Connors et al. 1985). Rather than retread their well-worn terrain, we offer the following summative observations of the extant state-of-the-field:

1. There seems to be no single biological or psychological imperative that dictates a "minimum space" demand for human habitation. (In this regard, a wry Plains Indian legend from frontier days ends with the observation that the "white man really needs only enough space in which to bury him.")

2. None of the dozens of simulation studies or experiences with analogous and precedent spacecraft environments have successfully separated out contributions of habitat volume and geometry from influences of ambient qualities of the setting and other intangibles

of habitability.

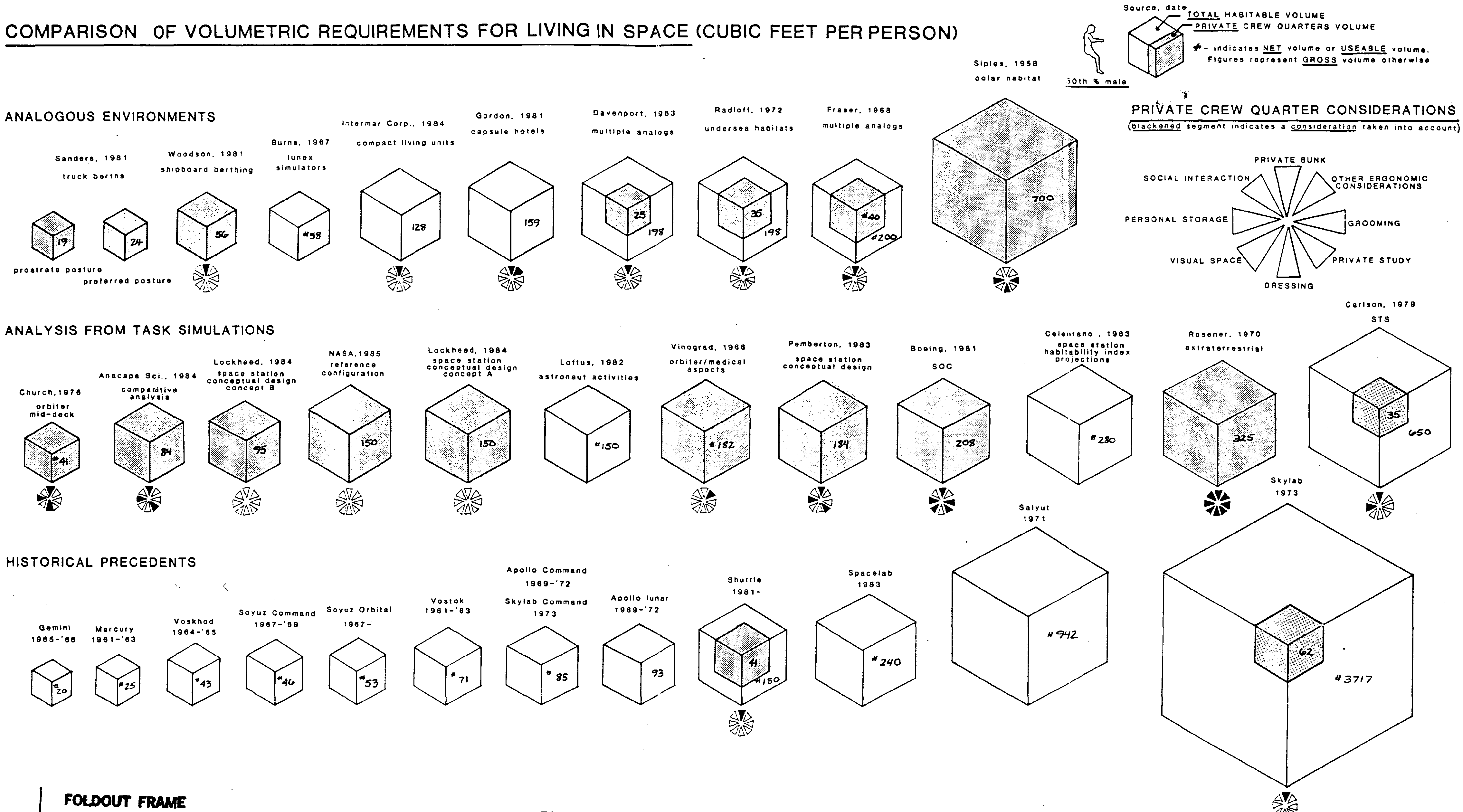
3. The measurement of sheer physical space in any terms of "habitable volume," "free volume," or "floorspace" is not sufficient to characterize the behavioral, psychological and social consequences that accrue from the available physical space. The human experience of a spatial medium is neither captured nor predicted by physical measures alone.

4. Where volume or geometry requirements have been systematically derived, their basis lies exclusively within considerations of static anthropometrics (e.g., 5th centile female---95 centile male) and/or simple body motions (e.g., a rotation about a body axis). While psychological, visual, or social aspects of space are acknowledged, these are not quantitatively developed.

5. There is neither an evolving nor converging agreement on basic questions such as "How much private space does a person need?" or "How much habitable free volume should be allowed per person?" Figure 2 summarizes a variety of different kinds of habitability studies and design proposals. Private space assignments are seen to vary over approximately a ten-fold range, from 25 ft^3 to 250 ft^3.

Insert Figure 2

6. Generally, as figure 2 shows, the greater the number and variety of activities that a space is meant to enclose, the more capacious it ought



FOLDOUT FRAME

Figure 2: Volumetric Comparisons

2 FOLDOUT FRAME

to be. For private crew quarters, the discriminating question often is: "What else should a cabin volume support besides sleep?" Investigators who see the need for leisure activities or private interpersonal conversations there correspondingly assign more space.

7. Over the past twenty-five years, there has been no steady mutual enrichment between the aerospace-oriented habitability literature and the growing number of similar studies that comprise the environmental psychology and behavior-design research fields. Consequently, theory and methodology that could help operationalize habitability concerns have not been applied by researchers in either disciplinary context.

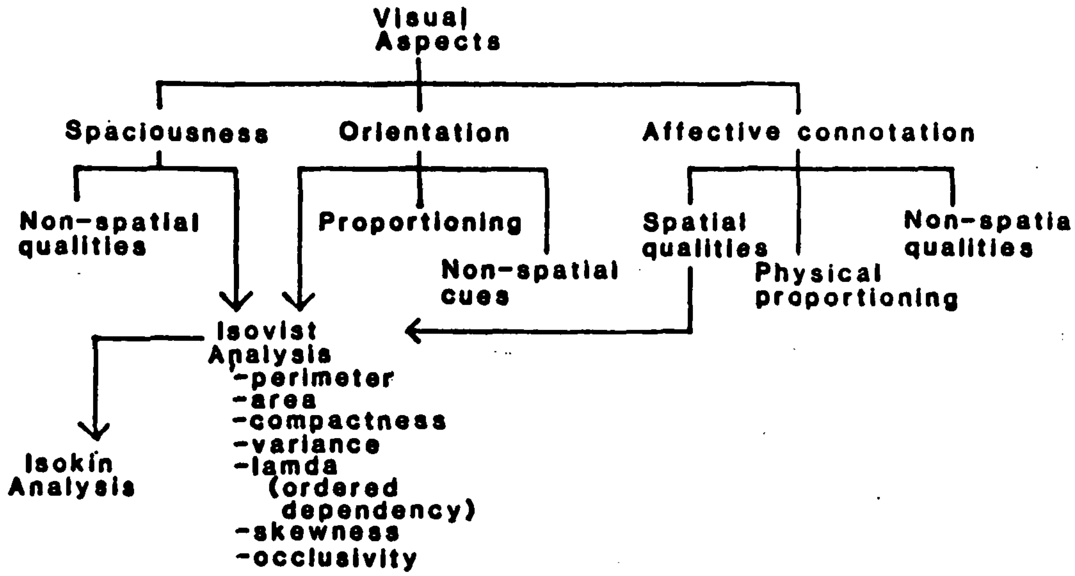
8. There are extremely rich sources of (mostly) anecdotal experiences from crews of Apollo and Skylab missions, Salyut living, and present STS orbital operations. Taken together, these provide a comprehensive basis for habitability assessment. But these anecdotes must be first organized into a more comprehensive model of spatial habitability.

In summary, our review of a wide range of literature suggests that there is not so much a need for data as there is a need for a conceptual net, an organizing model, that permits abstracting habitability guidelines for space stations. Such a model would aid in organizing the diverse observations, help resolve apparent conflicts across studies' results and suggest particular measures that most require further specification.

The remainder of this report presents and explores the major components of such a model. As mentioned earlier, the model was "assembled" by forming a database of incidents and observations which were then progressively grouped (and regrouped) into different content categories. Since such a collection of instances could be configured in a variety of ways, the tests for "Goodness of Fit" of a spatial habitability model should have both representative and heuristic considerations.

The model presented here is "good" to the extent that its aspects encompass all the data, exhibit internal consistency, and suggest new insights and innovative ways of problem solving. In particular, it ought to allow operationalization and measurement of those qualities acknowledged as important to habitability, but not yet systematically described. It ought to confirm, as Kurt Lewin once proposed, that "Nothing is so practical as a good theory."

VISUAL ASPECTS



We begin with the visual aspects of spatial habitability because:

a. these are most commonly noticed as available space decreases
b. these have been widely acknowledged, yet generally regarded as intangible
c. these are described by a formalism that is most intuitively appreciated in a visual sense, even though the theory can address kinesthetic and social logic issues.

The visual aspects of spatial habitaiblity span major considerations of spaciousness, orientation, and the affective connotation of spatial form.

Spaciousness is the perceived size/extent of an enclosure. Orientation refers to visual cues from either the geometry or interior rendering of an enclosure that aid "vertical referencing" or body positioning under zero g. The affective connotation of an enclosure deals with emotional messages conveyed by the enclosure's size and shape. Just as the word "mother" can denote a female parent, it also connotes warmth, tenderness and nurturance qualities. Spaces carry analogous messages for their users.

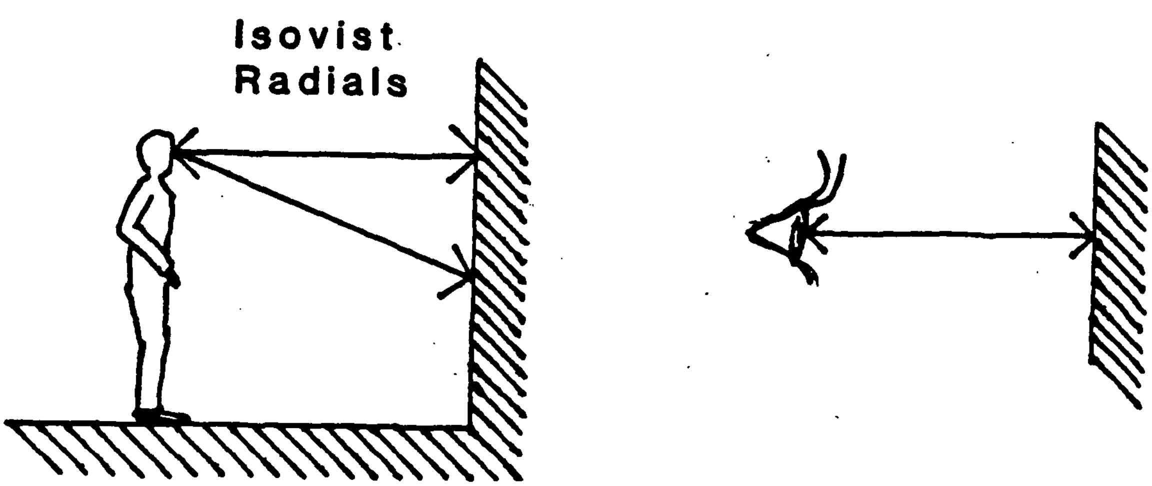
As the structural graphic shows, there are non spatial qualities that are involved with each of these visual aspects. They include surface finishes and colors, and how the space is rendered by light. In a well-designed room, such qualities are carefully arranged to work <u>with</u> the overall impression that the volume and geometry convey. Though the scope of this study was limited to considerations of volume and geometry, a comprehensive approach to visual spatial habitability must eventually include such surface and space-rendering details.

Proportioning of a space refers to the geometric proportions of the surfaces that enclose the space. A well-known example is the use of the "golden mean" or "divine" proportion in classical architecture (Huntley 1970; Pedoe 1976; Doczi 1981). However, the connection between preferences for and the functional impacts of proportions seems not to have been well investigated. Indeed, when proportioning is most often considered, it is in terms of the volume of space enclosed, and not in terms of the measure of the enclosing elements. The effect of spatial proportions is treatable by Isovist Analysis (see next paragraph). Lone surface proportions of the enclosing elements were not generally analyzed further in this investigation since they seem mostly to apply to situations well outside the context of habitability concerns (e.g., the view of a building facade from a distance). Proportioning is only included in our model graphic as an acknowledgment of potential future uses for this concept, particularly as it may apply to detail design.

The fundamental tool for the perceptual analysis of spatial volume is the Isovist. Isovist analysis was first developed by Michael Benedikt and some collaborators at the University of Texas at Austin (Benedikt 1977; Benedikt 1979; Davis and Benedikt 1979). Its origins lie in J. J. Gibson's theories of visual perception (Gibson 1966), but it is not necessary to ascribe to such theory in order to use the isovist instrumentally

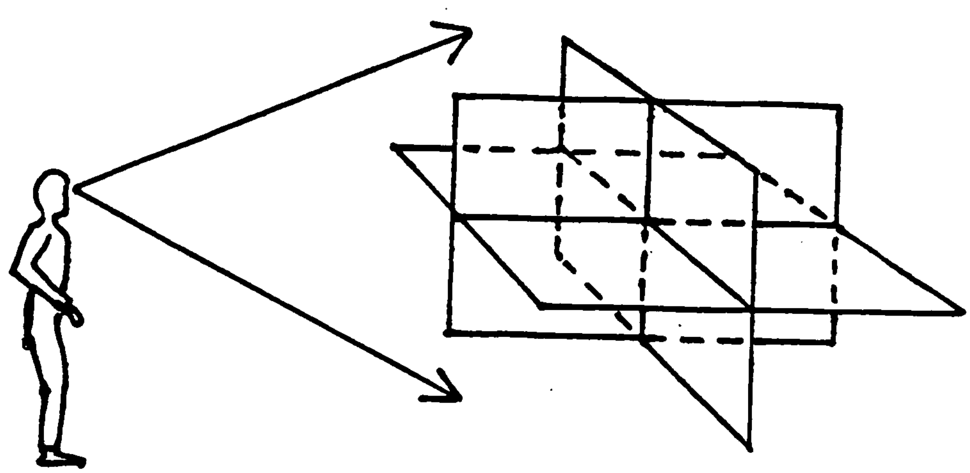
The Isovist Model

The isovist is the set of all points visible from a given vantage point. It is, succinctly, a location-specific pattern of visibility. Imagine that rays emanate from the viewer's eye, and proceed until they intersect some occluding edge or opaque surface (as in the diagram below). As the viewer's



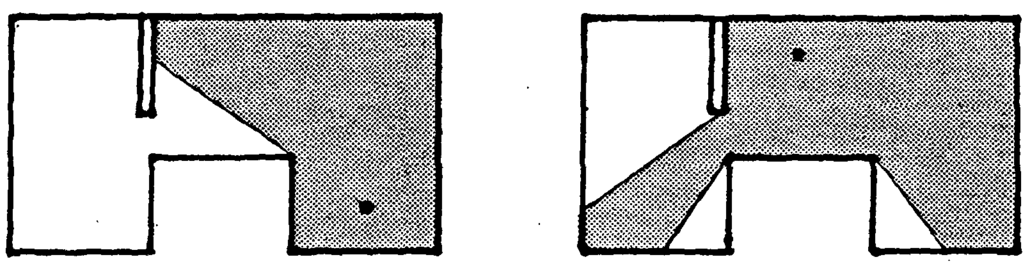
eye moves, such rays literally fill the space about the observer, as long as they are not intercepted by a solid object. For example, we cannot see the space below our desktop as we write, so that space would not be in our isovist. But all of the points that are connected by the rays are in the isovist, so that an isovist is a "(view)point and a set of surfaces such that the surfaces are wholly visible from that point" (Benedikt 1979, pg. 49).

The imaginary rays whose endpoints link observer and environment are called isovist radials. These radials fill observable, three-dimensional space. We can analytically treat the isovist in terms of its two-dimensional sections. If needed, each full isovist can be built up by combining the measures of three two-dimensional sections taken through the eye point of the observer.



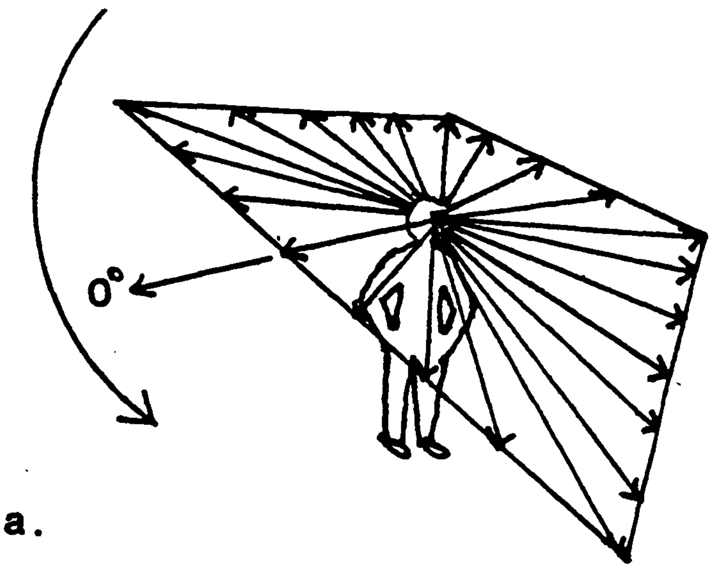
In architectural spaces that are "plan organized," a single horizontal section through the isovist at eye level can be used as the source of study without too great a loss of ecological validity. Other section's characteristics may also be added as needed and hopefully, someday, available computing power might allow analysis of the total isovist volume.

Isovists are analyzed in terms of the distributional characteristics of their radials. The graphic below shows two horizontal section (plan) isovists of an observer (marked by a dot) in the same environment. The cross-hatched area is that plane filled by isovist radials. The visible portion of the environment available to an observer changes with his or her position.

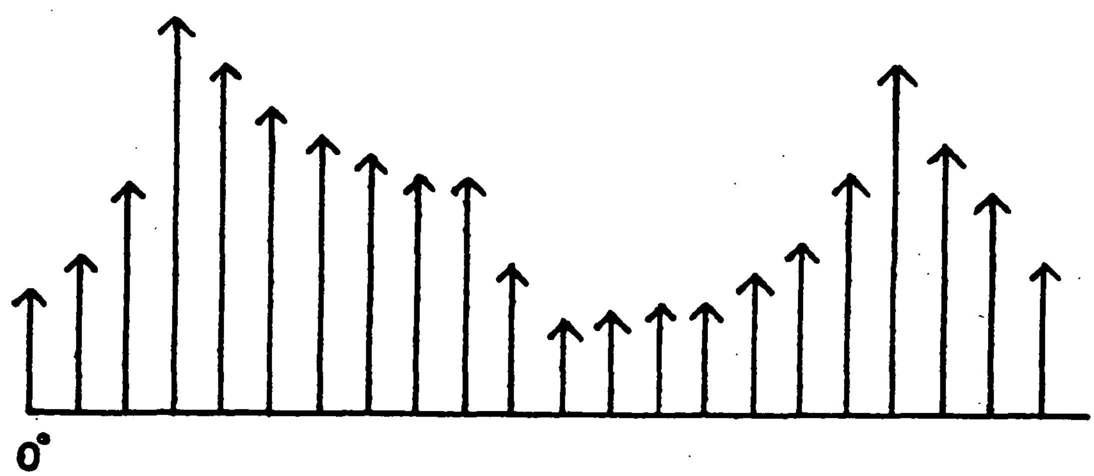


Plan isovists are commonly taken through a full 360° to represent an observer's rotational capability, but the subsequent analysis remains the same if a lesser spanning angle is used to represent a restricted or preferred cone of vision. Our investigation has used both full and restricted isovists, as the occasion warranted.

Imagine a full 360° isovist, with radials schematically illustrated on the next page:



a.



b.

Now, imagine that starting from due right of the observer, we take the radials and lay them out side by side, as the illustration shows. If we now make a frequency distribution of the radial lengths, we have the data basis for investigating several different distributional measures that describe the optical properties of the visible space. In particular, we can define and calculate the following spatial measures of the isovist:

AREA (A): The amount of space which can be seen from a vantage point X and conversely within which the vantage point X is visible.

VISIBLE PERIMETER (P): The length of the real surface visible boundary which can be seen from X.

OCCLUSIVE PERIMETER (Q): The length of the nonvisible radial component of the total isovist boundary.

VARIANCE (M_2): The second moment about the mean of the isovist radial lengths. Variance measures the dispersion of the isovist perimeter in relation to X.

SKEWNESS (M_3): The third moment about the mean of the isovist radial lengths. Skewness measures the asymmetry of the dispersion of the perimeter in relation to X.

COMPACTNESS (C): A measure of shape and complexity. It is the ratio of perimeter to area, P^2/A.

CIRCULARITY (N): Equals 1 when the isovist is a disc, and >1 otherwise. It is the square of the boundary of the isovist (including occluding radials), divided by 4 pi times the Area of the isovist. It is another measure of compactness/complexity.

LAMBDA: Measures first-order sequential dependencies. It is sensitive to the absolute rate of change between lengths of successive isovist radials. If radials alternate substantially between short and long lengths, lambda will be >1.00. Where successive radials have low rates of change, lambda will be <1.00. This measure is a way of getting back to the "pattern" information inherent in the isovist that other statistical measures ignore.

Adaptations of the above measures are also possible, such as M_2/A, which is the "coefficient of variation" in statistical terms.

These measures do not exhaust the list of possibilities. They were chosen because they seem to capture many obvious characteristics of visual space, and because several findings of earlier studies are easily interpreted within their context. All of these measures are insensitive to surface finishes such as color, texture and mirrors, as well as how the space is rendered by light. This makes the isovist in itself an insufficient tool for describing all of those characteristics that may affect perceptual judgments. But it does permit a direct assessment of the volume and geometry of visible space, which is of immediate concern to space station habitability.

By itself, isovist theory is neither a solely optical nor psychological description of visible space. But it is psychophysical by design, in that its unit of analysis--the isovist radial--has one endpoint defined by the eye of the observer and the other by a point in the environment. The perceptual validation of isovist theory, therefore, depends both on demonstrating that its measures vary in the ways they reasonably should, and on linking the measure changes with changes in observer judgments or behavior.

A close inspection of a few examples helps convey some feeling for isovist measures and how they vary with change of position and shape of an enclosure. Figure 3 shows the plan isovist of an observer standing in the middle of a perfectly cylindrical room. (These and other test configurations utilize a 'standardized' area of 15 ft^2 corresponding to the section through a volume of 105 ft^3 with a constant 7-foot height.)

Insert Figure 3 here

Notice that for this observer, all isovist radials are equivalent to a circle's radians. The isovist has no variance, skewness, or occlusivity. Circularity is minimal and compactness equals, as expected, 4 pi, which is also "minimal" in terms of this measure (although it indicates the <u>most</u> compact two-dimensional figure).

When the observer moves to the boundary of the cylindrical chamber, as indicated by the + in figure 4, his/her visual field becomes decidedly more interesting.

Insert Figure 4 here

Variance and skewness both rise with the incidence of "long radial" views. Note that lambda (ordered dependency) rises just a little--showing increased complexity--while compactness and circularity stay the same. The latter two measures are sensitive to only the total visible perimeter and areas of the isovist, which has remained unchanged by this change in position. When an entire, simple environment is visible to an observer under that observer's translation, some characteristics of the spatial

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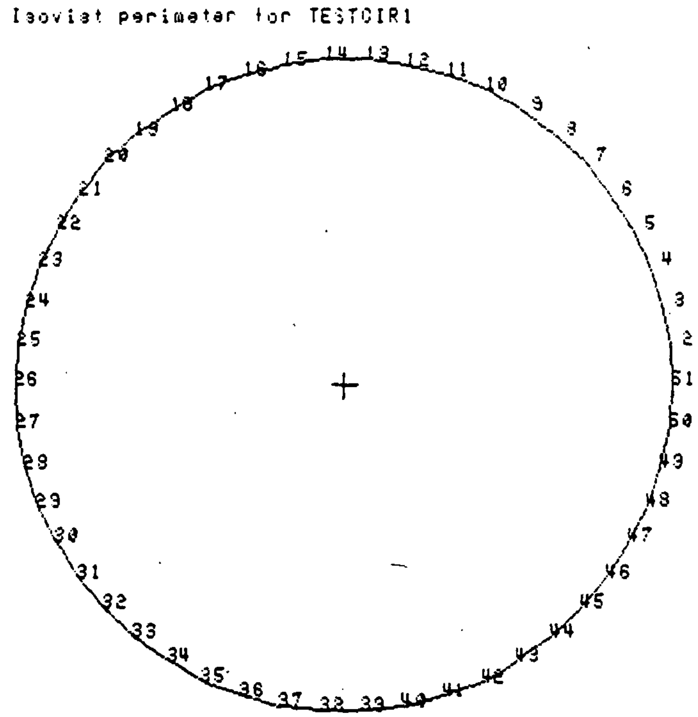

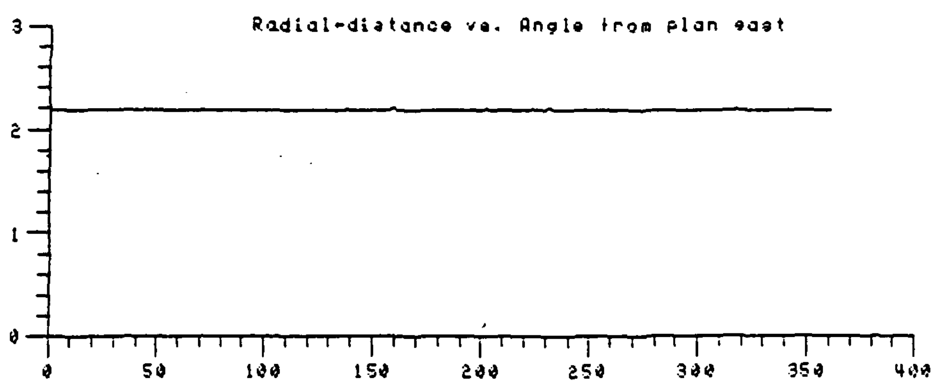

ISOVIST file TESTCIR1		Un-rotated position.	
Isovist Area (A) =	15.006	Variability (lamda) =	0.354
Total Perimeter (T) =	13.743	Compactness (C) =	12.536
Occlusive perimeter(Q)=	0.000	Circularity (N) =	1.002
Visible Perimeter (P) =	13.743	Q/P =	0.000
R-min =	2.176	Q/T =	0.000
R-max =	2.194	M2/A =	0.000
R-mean =	2.185	M3/A =	0.000
Standard Deviation =	0.003		
Variance (M2) =	0.000		
Skewness (M3) =	0.000		

Figure 3

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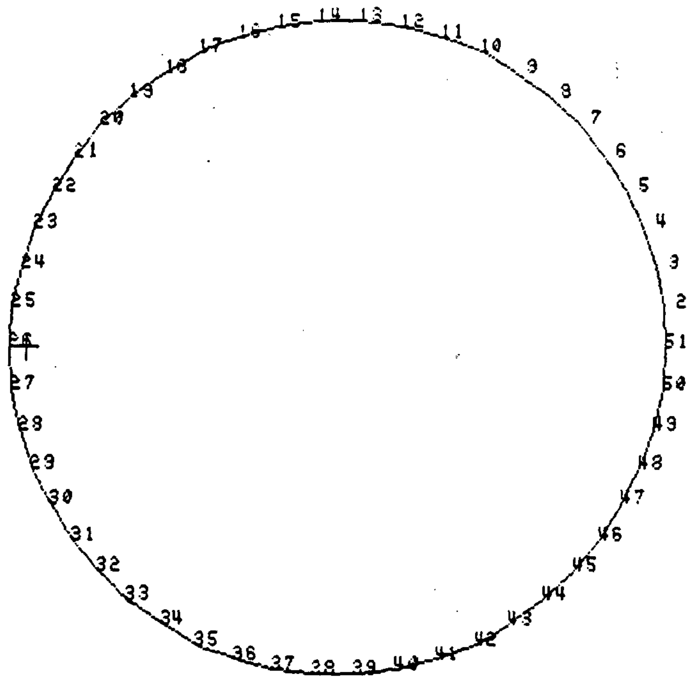
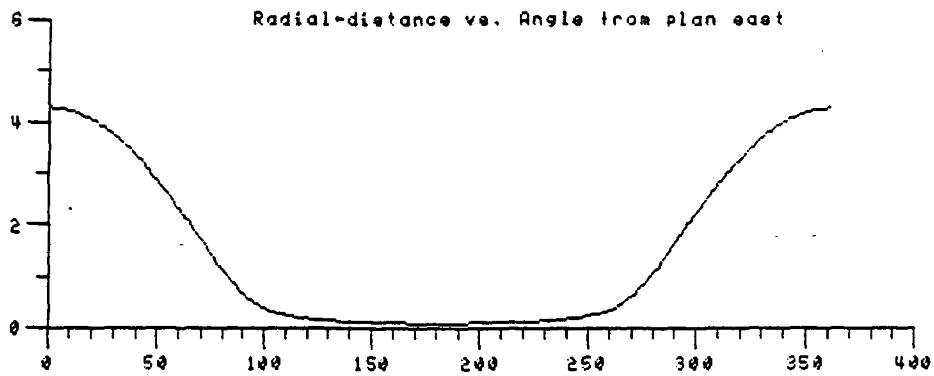
Isovist perimeter for TESTCIR2





ISOVIST file TESTCIR2	
Isovist Area (A) =	15.006
Total Perimeter (T) =	13.743
Occlusive perimeter(Q)=	0.000
Visible Perimeter (P) =	13.743
R-min =	0.100
R-max =	4.280
R-mean =	1.522
Standard Deviation =	1.569
Variance (M2) =	2.461
Skewness (M3) =	2.381

Un-rotated position.	
Variability (lamda) =	1.226
Compactness (C) =	12.586
Circularity (N) =	1.002
Q/P =	0.000
Q/T =	0.000
M2/A =	0.164
M3/A =	0.159

Figure 4

experience remain invariant, while others do not. For comparison, examine the isovist in the pie-shaped enclosure pictured in figures 5 and 6.

Insert Figures 5 and 6 here

With area equal to the circular isovist and with the same relative position, there are correspondent increases in visible perimeter and elongation (measured by circularity and compactness) of the visual field. Somewhat surprisingly, the circle continues to show slightly higher variance and lambda measures. This is induced by the presence of curved walls which show more total and successive variation in isovist radials than straight walls which recede from an observer.

Other properties of isovists become manifest if one takes an imaginary walk across the pie-shaped chamber. Starting with figure 7, the observer moves along the axis of bilateral symmetry in figures 7 through 9. Note that variance and skewness decrease markedly with shifts toward the center of the room. This is a general result, as the distribution of isovist radials tends to become more uniform from the center of enclosed spaces. Of course, when there is no occlusivity, compactness and circularity stay the same. Lambda also drops toward the middle of a space, but not as precipitously as variance or skewness. Lambda also increases when one is close to a curved, enclosing surface as in figure 9.

Insert Figures 7 thru 9

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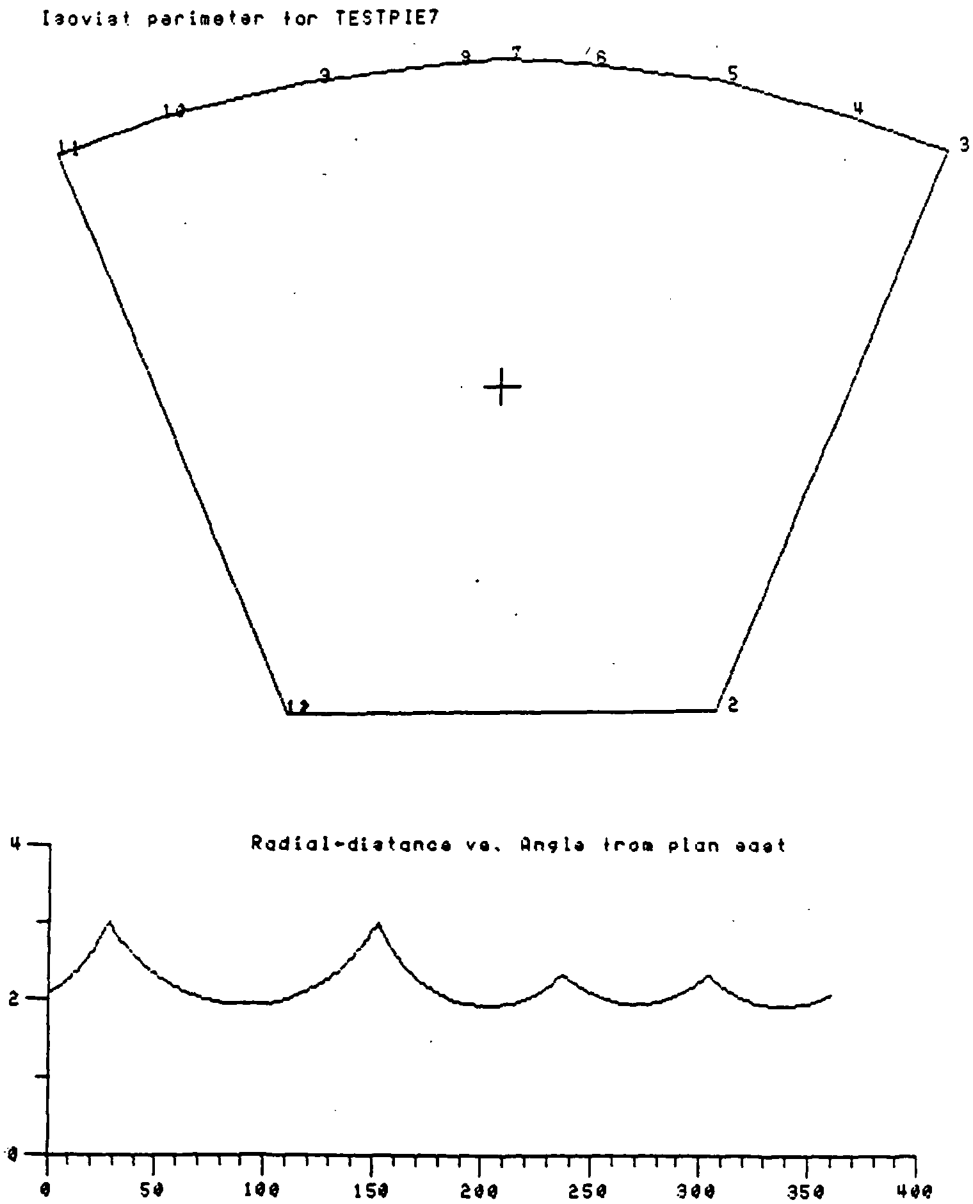
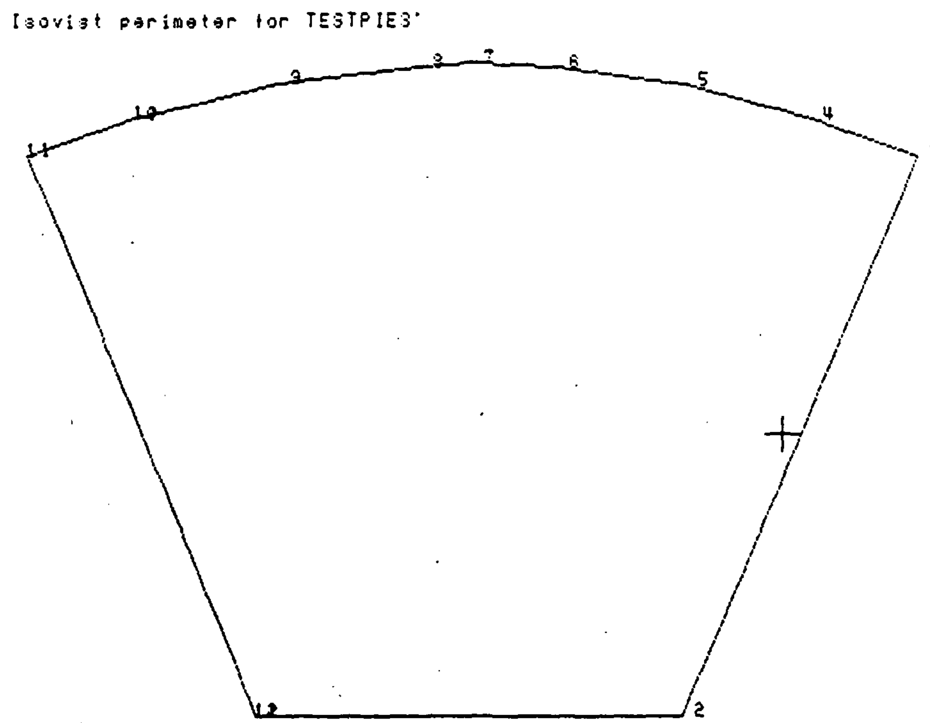
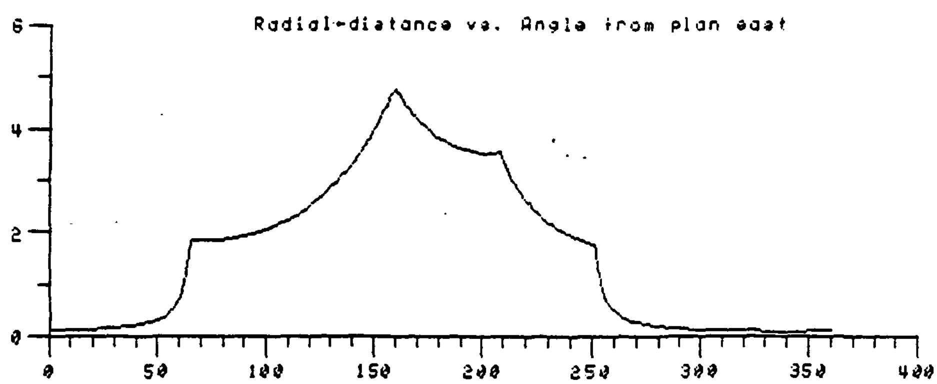


ISOVIST file TESTPIE7	
Isovist Area (A) =	14.974
Total Perimeter (T) =	15.223
Occlusive perimeter(Q) =	0.000
Visible Perimeter (P) =	15.223
R-min =	1.915
R-max =	2.996
R-mean =	2.187
Standard Deviation =	0.265
Variance (M2) =	0.070
Skewness (M3) =	0.025

Un-rotated position.	
Variability (lamda) =	0.898
Compactness (C) =	15.476
Circularity (N) =	1.232
Q/P =	0.000
Q/T =	0.000
M2/A =	0.005
M3/A =	0.002

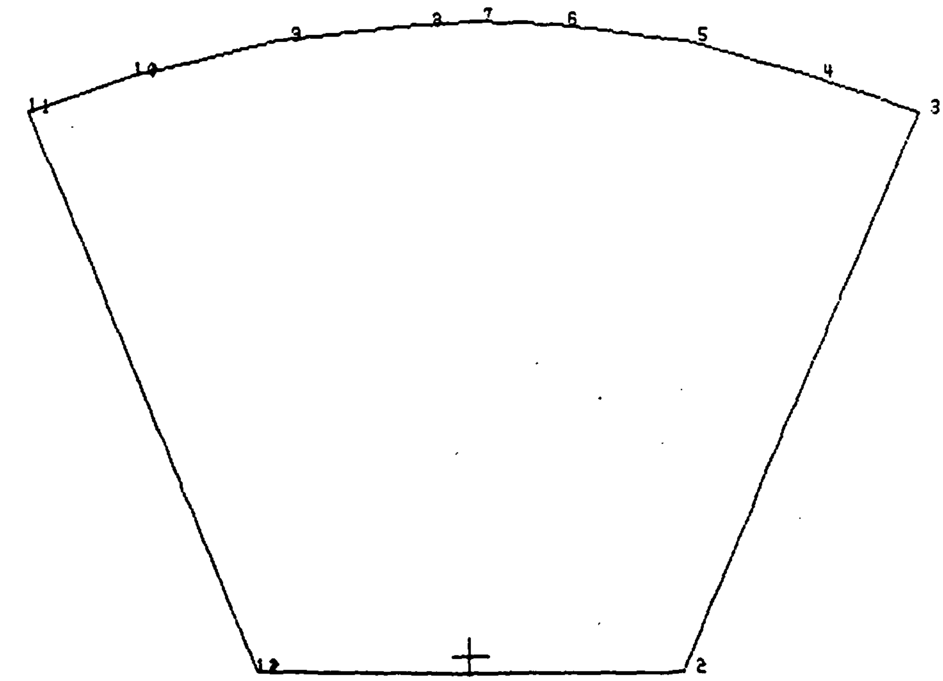
Figure 5

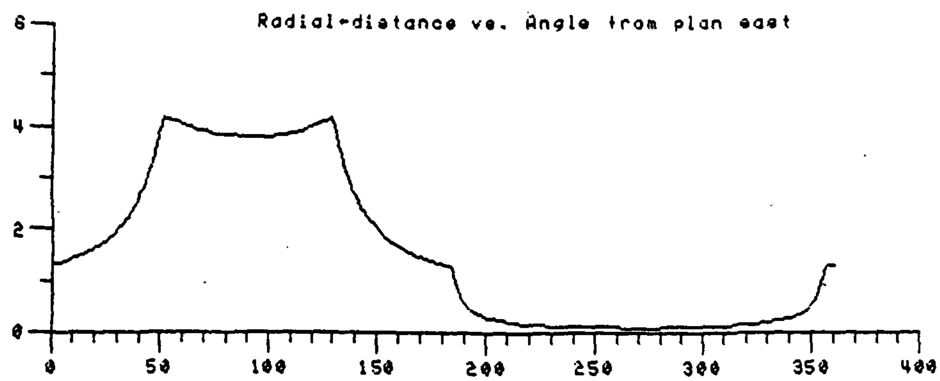




ISOVIST file TESTPIE3		Un-rotated position.	
Isovist Area (A) =	14.374	Variability (lamda) =	1.006
Total Perimeter (T) =	15.223	Compactness (C) =	15.476
Occlusive perimeter(Q)=	0.000	Circularity (N) =	1.232
Visible Perimeter (P) =	15.223	Q/P =	0.000
R-min =	0.100	Q/T =	0.000
R-max =	4.772	M2/A =	0.146
R-mean =	1.608	M3/A =	0.096
Standard Deviation =	1.479		
Variance (M2) =	2.187		
Skewness (M3) =	1.435		

Figure 6





ISOVIST file TESTPIE1

Isovist Area (A) =	14.974
Total Perimeter (T) =	15.223
Occlusive perimeter(Q) =	0.000
Visible Perimeter (P) =	15.223
R-min =	0.100
R-max =	4.188
R-mean =	1.569
Standard Deviation =	1.518
Variance (M2) =	2.303
Skewness (M3) =	1.950

Un-rotated position.

Variability (lamda) =	0.326
Compactness (C) =	15.476
Circularity (N) =	1.232
Q/P =	0.000
Q/T =	0.000
M2/A =	0.154
M3/A =	0.130

Figure 7

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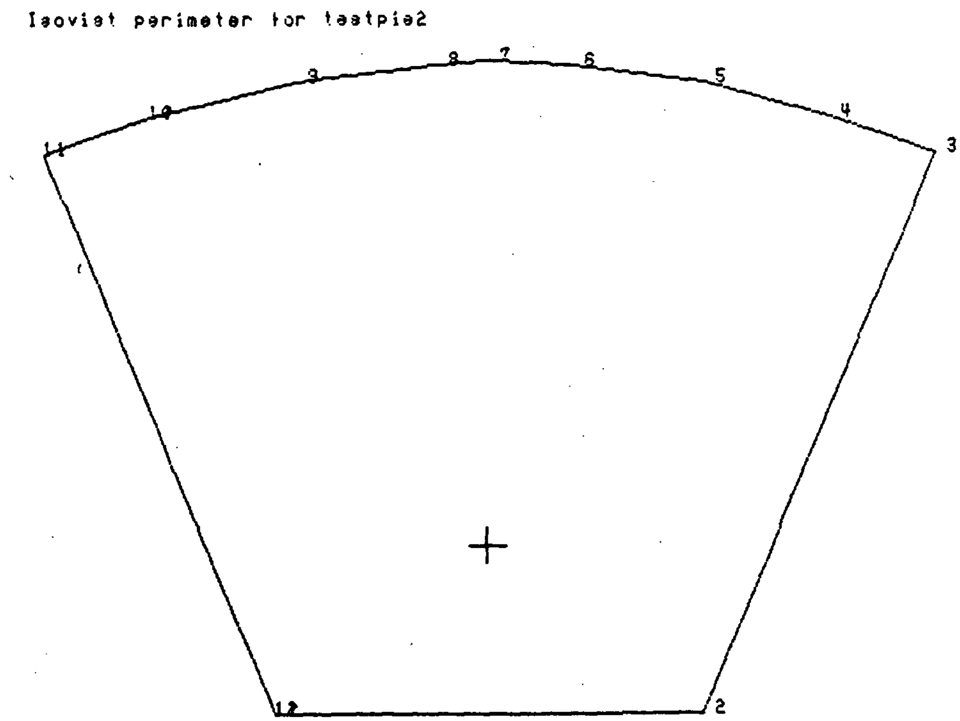

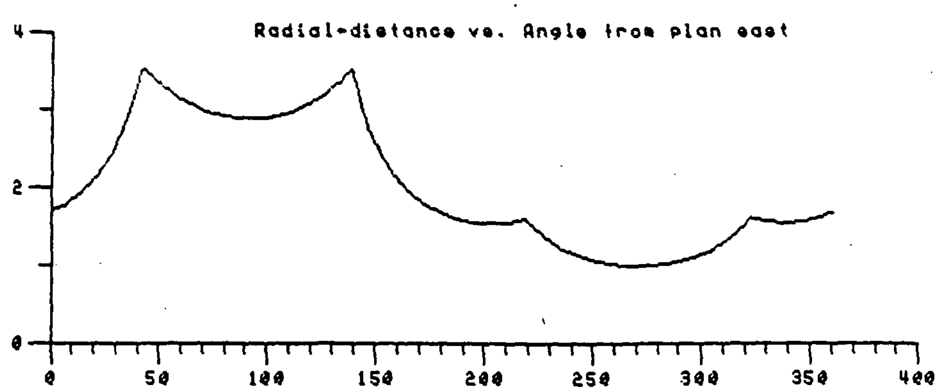

ISOVIST file testpie2		Un-rotated position.	
Isovist Area (A) =	14.974	Variability (lamda) =	0.924
Total Perimeter (T) =	15.223	Compactness (C) =	15.476
Occlusive perimeter(Q)=	0.000	Circularity (N) =	1.232
Visible Perimeter (P) =	15.223	Q/P =	0.000
R-min =	1.000	Q/T =	0.000
R-max =	3.531	M2/A =	0.043
R-mean =	2.030	M3/A =	0.013
Standard Deviation =	0.802		
Variance (M2) =	0.644		
Skewness (M3) =	0.197		

Figure 8

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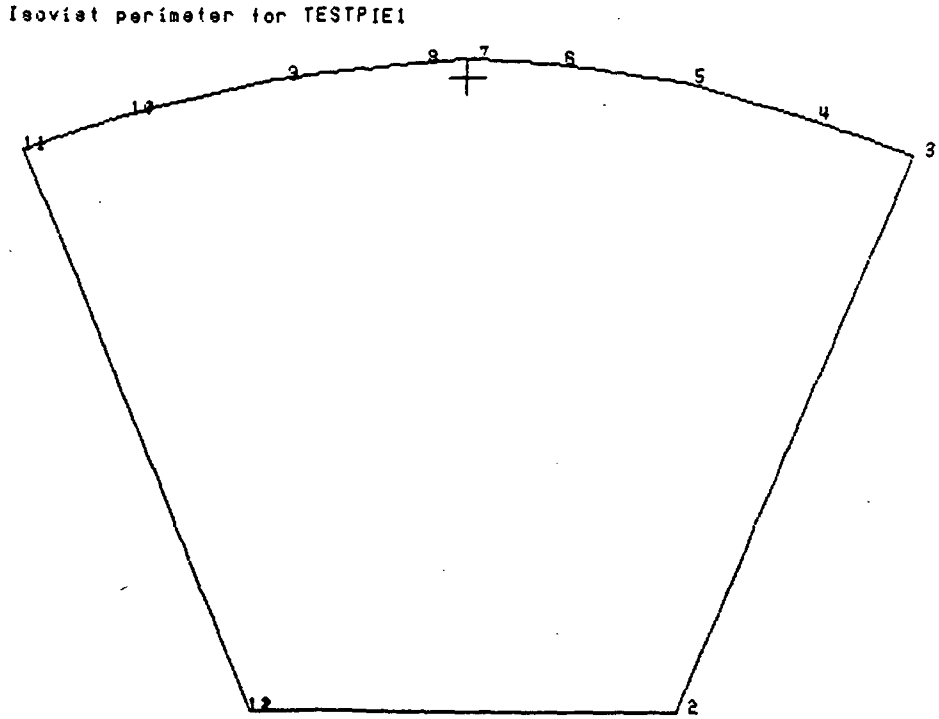
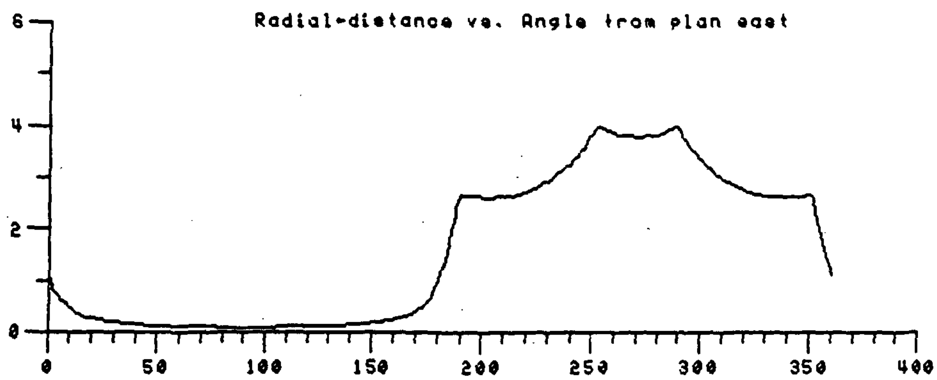




ISOVIST file TESTPIE1		Un-rotated position.	
Isovist Area (A) =	14.974	Variability (lamda) =	0.975
Total Perimeter (T) =	15,223	Compactness (C) =	15.476
Occlusive perimeter(Q)=	0.000	Circularity (N) =	1.232
Visible Perimeter (P) =	15.223	Q/P =	0.000
R-min =	0.100	Q/T =	0.000
R-max =	3.985	M2/A =	0.145
R-mean =	1.809	M3/A =	0.052
Standard Deviation =	1.476		
Variance (M2) =	2.178		
Skewness (M3) =	0.784		

Figure 9

Figures 10 and 11 show the observer's isovist from two corners of the space. This is the condition that makes variance and skewness maximal, but not lambda, which is driven by sequential dependency.

Insert Figures 10 and 11

A better demonstration of lambda's sensitivity is shown in figures12 to 15, where spanning angles are specified to show the effect of views toward and along straight and curved walls. For views of equal-length perimeters, lambda is greater when one looks toward or along a curved surface, which produces nonlinear sequential dependencies in successive radial lengths.

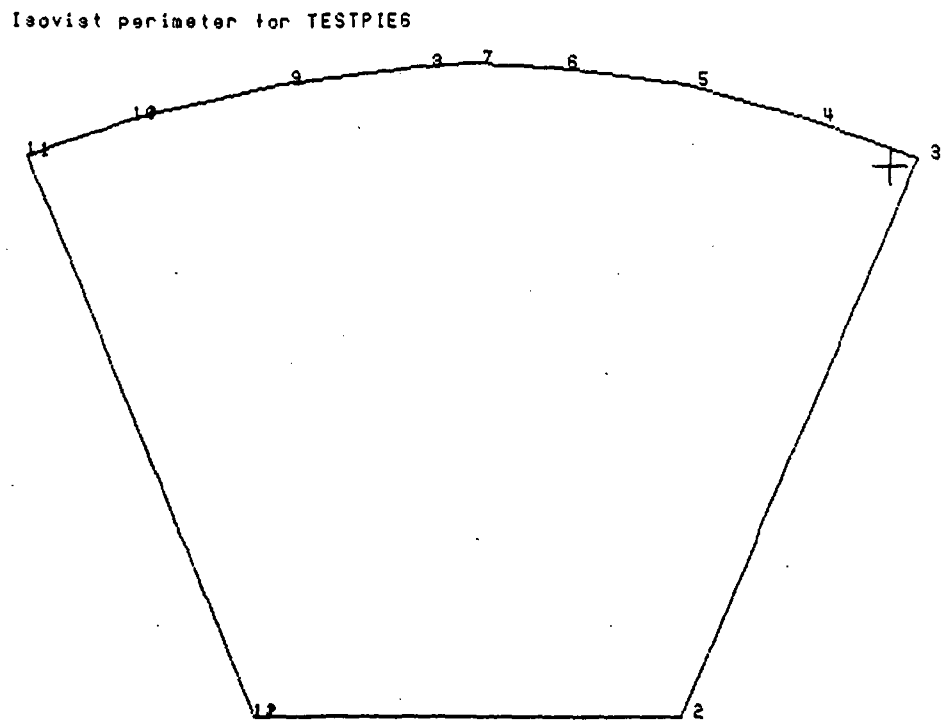
Insert Figues 12 thru 15

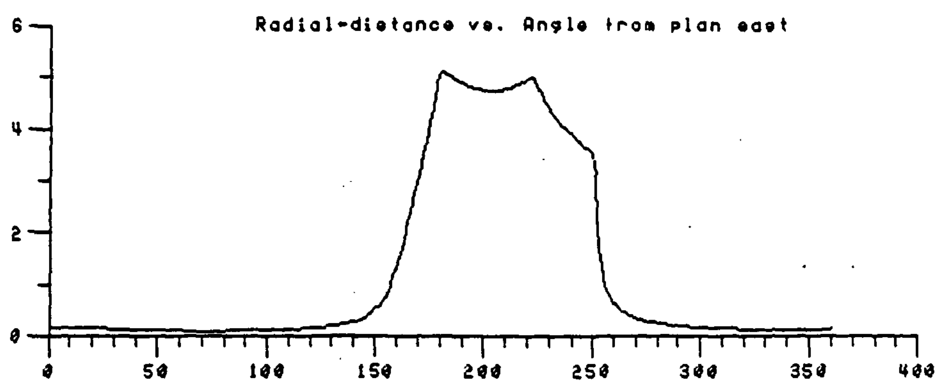
Figures 16 and 17 are a comparison of two spaces that adjoin a corridor. Figure 16 is a commonly encountered room configuration. Figure 17 is a proposed crew quarter from Boeing's SOC (1981). Both of these illustrate the effect that singular long (zen) views induce on a space. There are concomitant increases in area, variance, skewness, occlusive perimeter, and elongation.

Insert Figures 16 and 17

Generally, we can summarize the effects of different vantage points in enclosures as follows:

Variability and skewness of view increase near the boundaries, and particularly, the corners of a space.





ISOVIST file TESTPIE6	
Isovist Area (A) =	14.974
Total Perimeter (T) =	15.223
Occlusive perimeter(Q)=	0.000
Visible Perimeter (P) =	15.223
R-min =	0.100
R-max =	5.119
R-mean =	1.232
Standard Deviation =	1.802
Variance (M2) =	3.247
Skewness (M3) =	7.360

Un-rotated position.	
Variability (lamda) =	0.784
Compactness (C) =	15.476
Circularity (N) =	1.232
Q/P =	0.000
Q/T =	0.000
M2/A =	0.217
M3/A =	0.491

Figure 10

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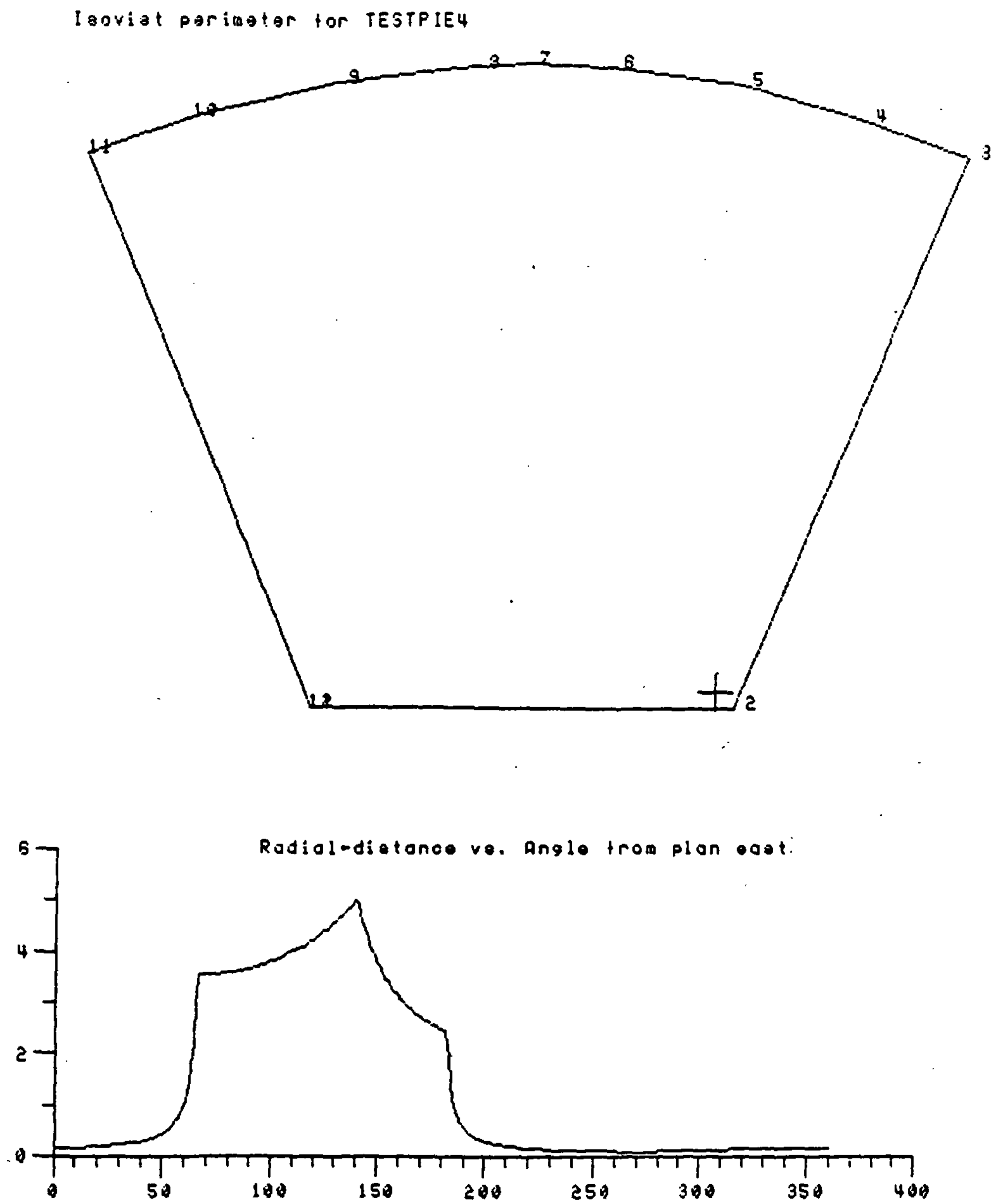


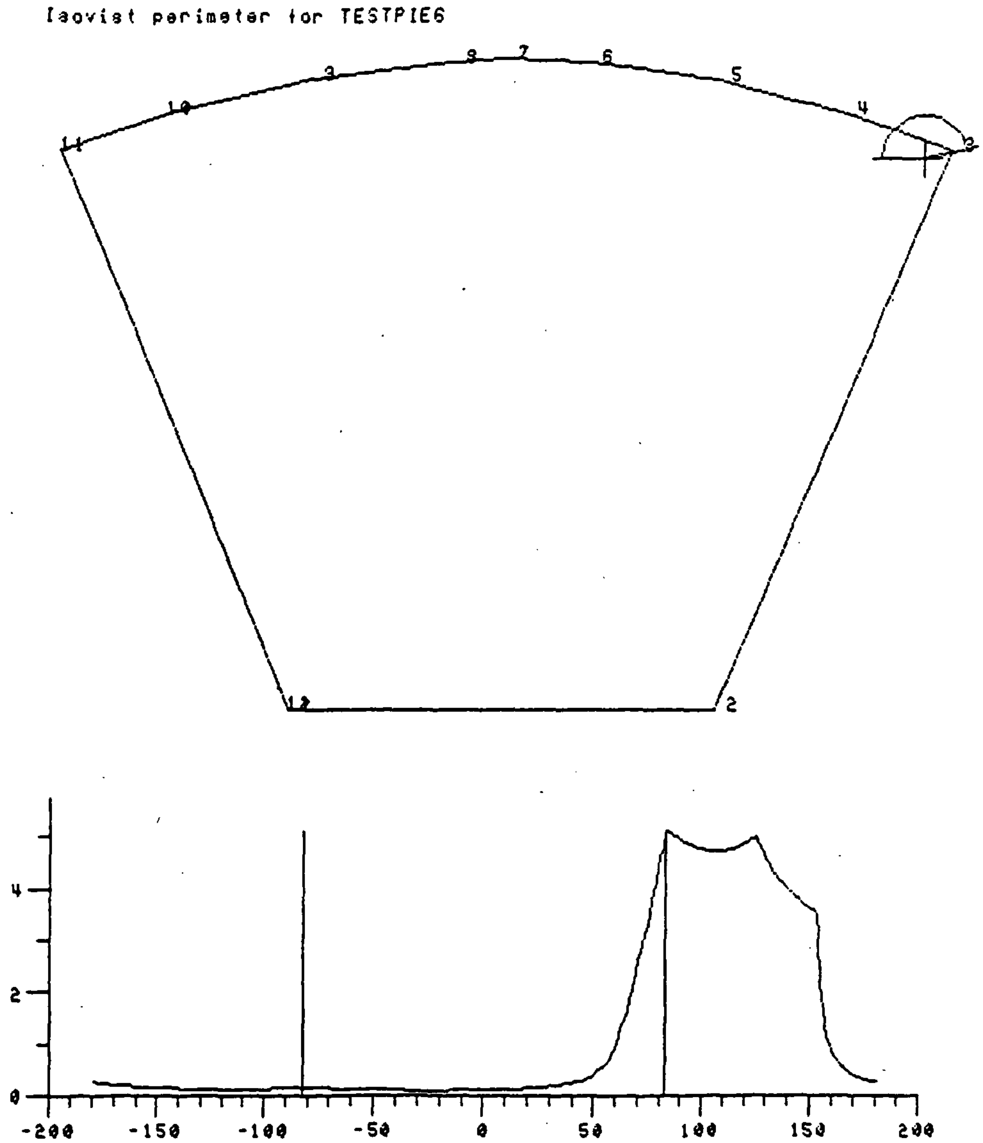
ISOVIST file TESTPIE4

Isovist Area (A) =	14.374
Total Perimeter (T) =	15.223
Occlusive perimeter(Q) =	0.000
Visible Perimeter (P) =	15.223
R-min =	0.100
R-max =	4.981
R-mean =	1.383
Standard Deviation =	1.689
Variance (M2) =	2.853
Skewness (M3) =	4.009

Un-rotated position.

Variability (lamda) =	0.361
Compactness (C) =	15.476
Circularity (N) =	1.232
Q/P =	0.000
Q/T =	0.000
M2/A =	0.131
M3/A =	0.268

Figure 11



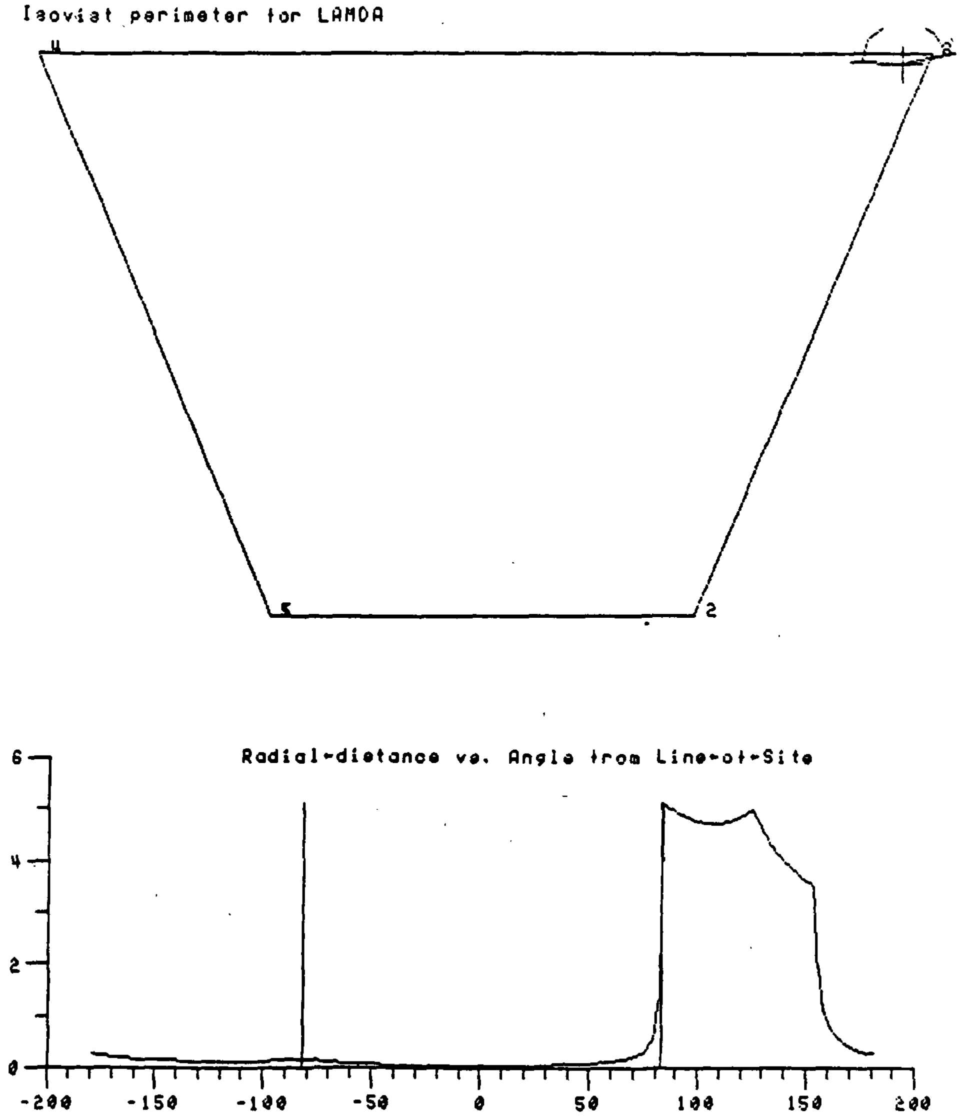
ISOVIST file TESTPIE6

Isovist Area (A)	=	1.876
Total Perimeter (T)	=	5.334
Occlusive perimeter(Q)	=	0.000
Visible Perimeter (P)	=	5.334
R-min	=	0.100
R-max	=	5.032
R-mean	=	0.545
Variance (M2)	=	1.075
Skewness (M3)	=	3.116

Spanning angles 14.0 to 179.0

Variability (lamda)	=	0.648
Compactness (C)	=	15.169
Circularity (N)	=	1.207
Q/P	=	0.000
Q/T	=	0.000
M2/A	=	0.573
M3/A	=	1.661

Figure 12



ISOVIST file LAMDA		Spanning angles 14.0 to 173.0	
Isovist Area (A) =	0.076	Variability (lamda) =	0.635
Total Perimeter (T) =	3.037	Compactness (C) =	120.705
Occlusive perimeter(Q)=	0.000	Circularity (N) =	9.605
Visible Perimeter (P) =	3.037	Q/P =	0.000
R-min =	0.050	Q/T =	0.000
R-max =	2.865	M2/A =	0.894
R-mean =	0.128	M3/A =	1.864
Standard Deviation =	0.261		
Variance (M2) =	0.068		
Skewness (M3) =	0.142		

Figure 13

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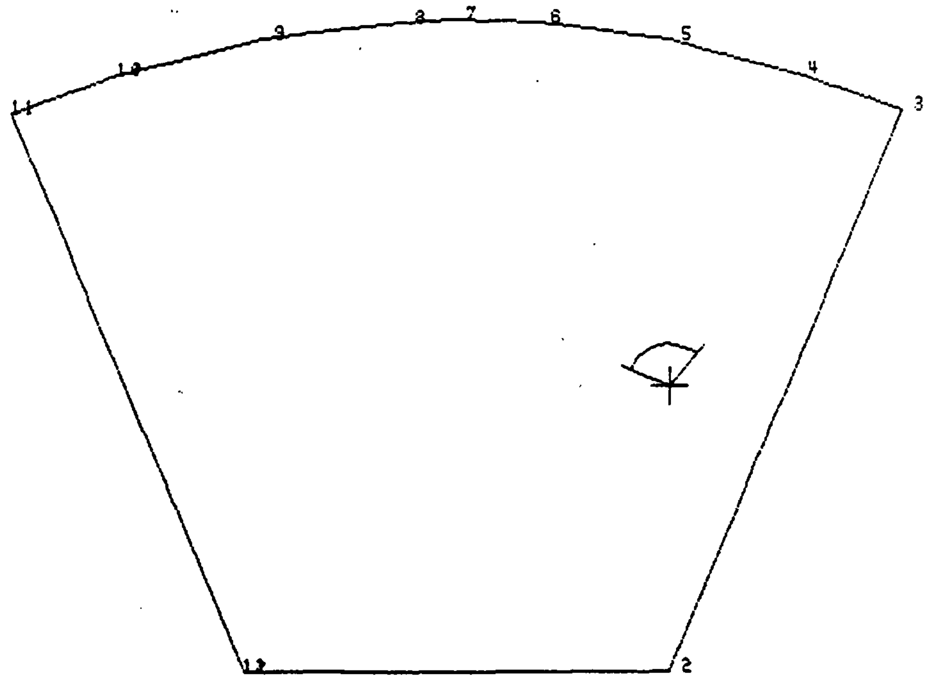
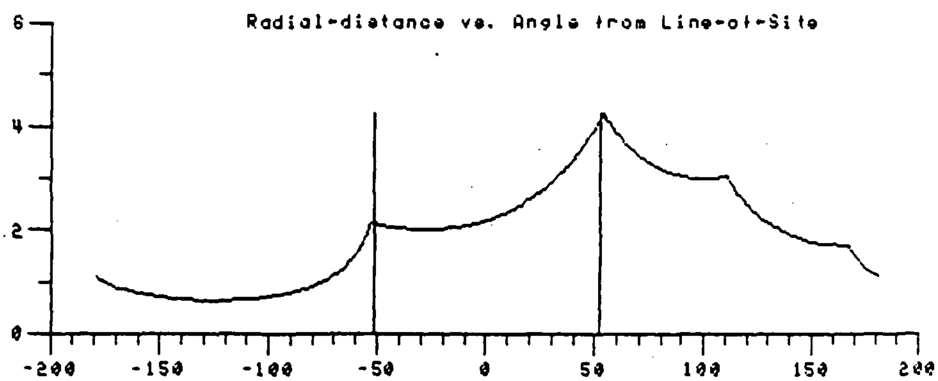
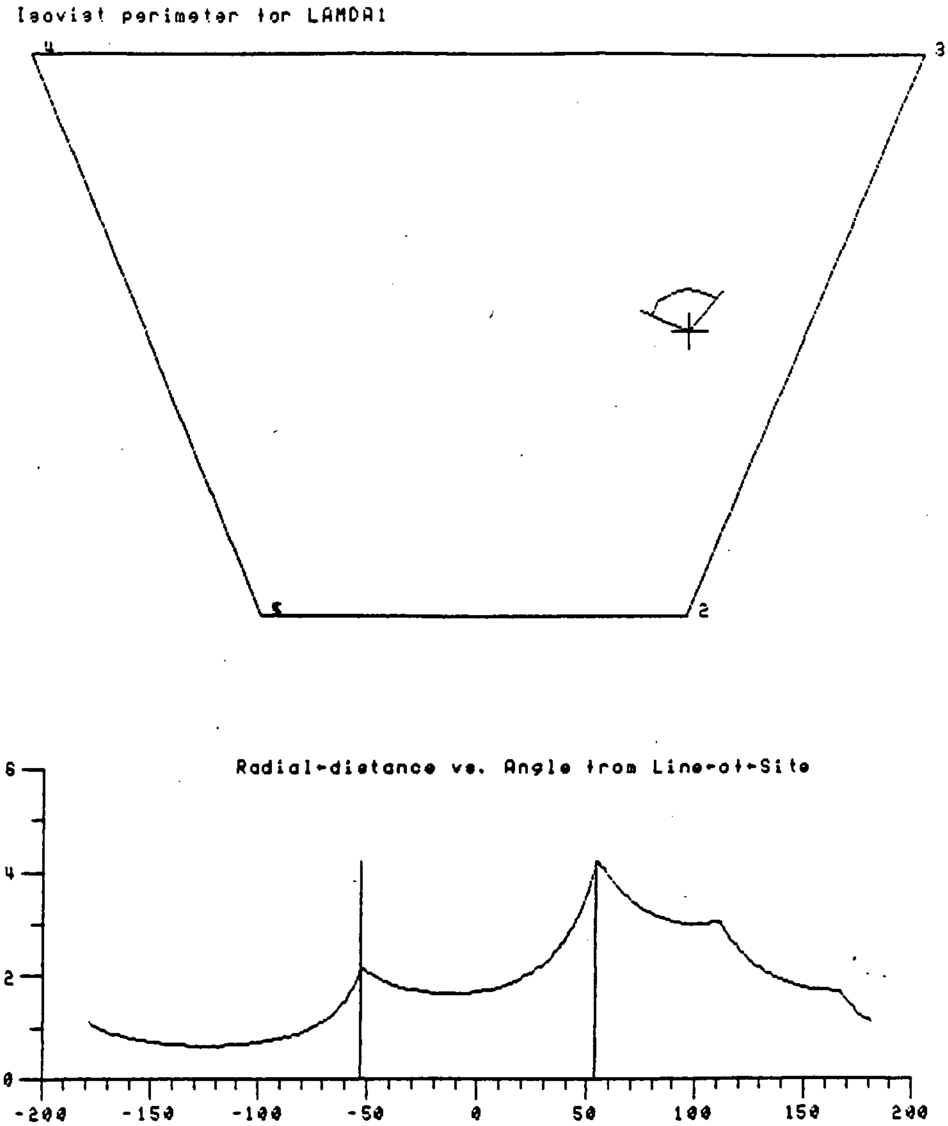
Isovist perimeter for TESTPIE3





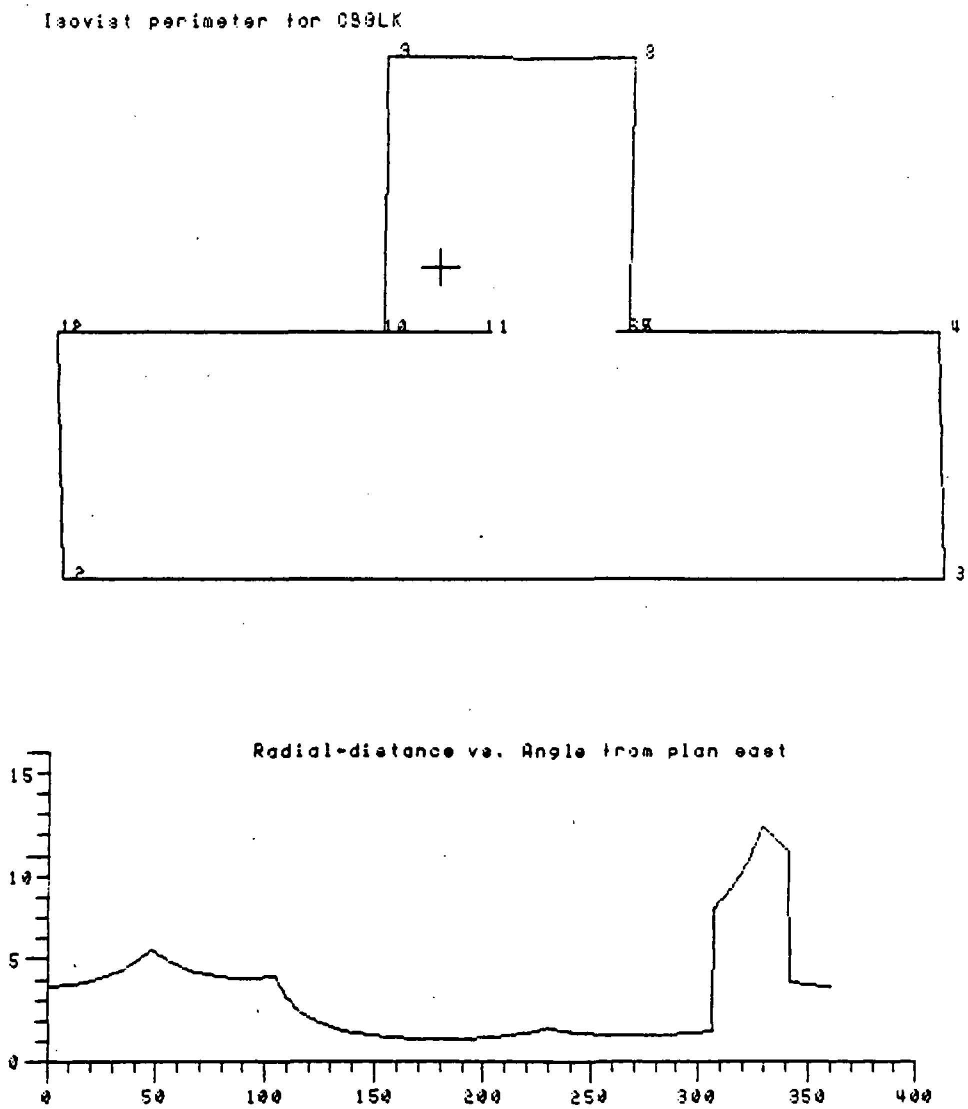
ISOVIST file TESTPIE3		Spanning angles 51.0 to 156.0	
Isovist Area (A) =	5.997	Variability (lamda) =	1.722
Total Perimeter (T) =	5.274	Compactness (C) =	4.637
Occlusive perimeter(Q)=	0.000	Circularity (N) =	0.363
Visible Perimeter (P) =	5.274	Q/P =	0.000
R-min =	1.999	Q/T =	0.000
R-max =	4.160	M2/A =	0.059
R-mean =	2.497	M3/A =	0.043
Variance (M2) =	0.353		
Skewness (M3) =	0.259		

Figure 14



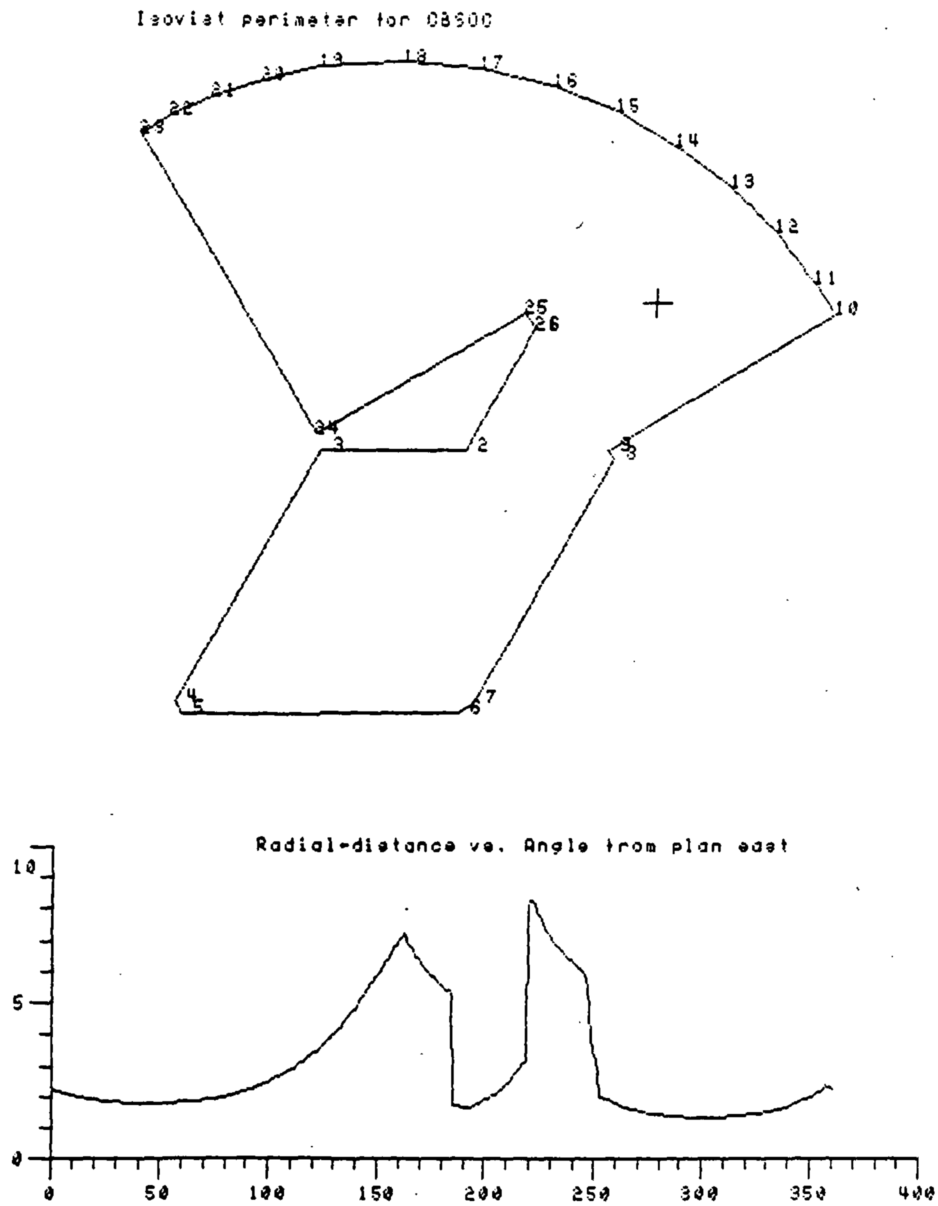
ISOVIST file LAMDA1		Spanning angles	50.0 to 156.0
Isovist Area (A) =	4.200	Variability (lamda) =	1.567
Total Perimeter (T) =	5.097	Compactness (C) =	6.187
Occlusive perimeter(Q)=	0.000	Circularity (N) =	0.432
Visible Perimeter (P) =	5.097	Q/P =	0.000
R-min =	1.650	Q/T =	0.000
R-max =	4.057	M2/A =	0.073
R-mean =	2.071	M3/A =	0.074
Variance (M2) =	0.306		
Skewness (M3) =	0.311		

Figure 15



ISOVIST file C8OLK		Un-rotated position.	
Isovist Area (A) =	51.581	Variability (lamda) =	0.392
Total Perimeter (T) =	37.395	Compactness (C) =	27.111
Occlusive perimeter(Q)=	12.478	Circularity (N) =	2.157
Visible Perimeter (P) =	24.916	Q/P =	0.501
R-min =	1.082	Q/T =	0.334
R-max =	11.388	M2/A =	0.124
R-mean =	3.179	M3/A =	0.507
Variance (M2) =	6.421		
Skewness (M3) =	26.132		

Figure 16



ISOVIST file CBSOC		Un-rotated position.	
Isovist Area (A) =	38.316	Variability (lamda) =	0.823
Total Perimeter (T) =	35.633	Compactness (C) =	33.146
Occlusive perimeter(Q)=	11.633	Circularity (N) =	2.638
Visible Perimeter (P) =	23.385	Q/P =	0.495
R-min =	1.319	Q/T =	0.326
R-max =	8.284	M2/A =	0.094
R-mean =	2.944	M3/A =	0.224
Standard Deviation =	1.893		
Variance (M2) =	3.584		
Skewness (M3) =	8.586		

Figure 17

Visible area increases from the boundaries or corners if the isovist is restricted to less than full rotation.

Movement to or from a window or opening not only changes visible area, but also the variance, occlusivity, and skewness of the view. Being close to a window expands the area of one's view, but occlusivity, skewness, and variance are subsequently diminished when compared to a position further away from the window.

Lambda (sequential complexity) is generally less near the centers of spaces, and particularly increases in views toward or along curved surfaces.

<u>Effects of Enclosure on Judged Volume and Spaciousness</u>

With the isovist measures as tools, it is now possible to ask, "What, if any, relation do these calculations have with perceived volume or sensed spaciousness?"

Psychological studies of perceived volume and spaciousness show a substantial, if unsystematic history of development (see Ankerl 1981, Chapter 14). The problem has been that, although many empirical manipulations were tested, no coherent, unifying model was used as a basis for investigation. Study here has been empirically, not theoretically, driven.

Arriving late on the scene, isovist theory provides the needed comprehensive model. But how well do the various isovist measures describe the empirical results? Consider the question about "perceived spaciousness" in an increasing order of complexity:

1. Does subjective, perceived space equal objective, physical space? Definitely not. Simple line illusions of relative size are reproducible in natural environments (Chapanis and Mankin 1967), and other illusions of perceived volume occur, such as the "rectangularity illusion" reported by Sadalla and Oxley (1984). Even the judged size of two-dimensional figures is due more to their relative complexity than to their area differences (Hitchcock et al. 1962).

In other words, it should be possible to manipulate geometric aspects of a room or enclosure in order to affect the occupant's perceived volume and/or spaciousness.

2. What factors related to room size and geometry have been shown to most affect judgments of spaciousness and/or volume?

a. Overall, judged size of a physical space seems nonlinearly related to physical size (Garling 1969). This seems due to growing errors of overestimation as the depth (away from a viewer) of a space increases (Gilinsky 1951).

Greatest deviations from nonlinearity, however, occur at visual distances larger than would be encountered in a space station interior. For room volumes up to $1000 m^3$, Innui and Miyata (1973) found that judged spaciousness was a power function of volume with exponent approximately = 1.00.

b. The shape of a room is a significant determinant of perceived volume.

Menchikoff (1975) discusses how rectangular rooms are perceived as having more volume than square rooms of actual identical volume. This impression increases with increasing rectangularity. Sadalla and Oxley (1984) independently confirmed this result and showed it to be independent of viewing position of the observer. Their results substantiate those of Innui and Miyata (1973), who found no differences in judged spaciousness depending on whether a rectangular model room was viewed from the long or short dimension.

For extreme rectangular spaces, with aspect ratios greater than 2.0:1.0, the illusory effect of greater volume seems to diminish with opportunity to explore the space (Menchikoff 1975). This diminution increases with increasing rectangularity (tested over a range of 1.5:1.0 to 3.0:1.0).

c. The height dimension of a room is that measure which is most often overestimated. This recalls the vertical/horizontal illusion (Chapanis and Mankin 1967) that appears operative in natural settings. Adults overestimate height by approximately 7% (Menchikoff 1975), while Garling's (1970;1969) studies estimate that the exponent for height in his power law model is less than that for depth and base. However, volume overestimation starts <u>earlier</u> than basic area overestimation, indicating that it is the overestimate of the height dimension that encourages the judged error.

It is entirely unkown whether this enhanced effect of perceived height will persist when a person actually traverses the vertical dimension, as one can in zero g.

d. As the elongation ratio of a volume increases so does the volume overestimation (Ankerl 1981). Generally, subjective volume can be seen as an inverse function of a space's compactness and the number of its axes of symmetry. Highly compact, symmetrical spaces should be judged as less spacious than irregular, elongated ones.

e. Distances judged along surface lines are overestimated with respect to those judged over "air" lines (Ankerl 1981).

This implies that when a room gives an observer the opportunity to look along a wall to another boundary wall, the boundary wall should be judged as further away than if it is seen from the same physical distance across the empty space of the room. Opportunities for view axes enhance sensed spaciousness.

3. Can isovist measures account for the empirical results on judged spaciousness?

Benedikt and Burnham (1985) provide the most explicit test of isovist theory as a descriptive model for judgments of spaciousness. In their first study, subjects judged pairs of model environments in terms of which member of the pair had more visible space. Their second study asked which had more total space. The model environments were constructed to vary on one isovist measure while holding other measures constant. The results showed that high values of area and variance and low values of visible perimeter and occlusivity were associated with judgments of greater perceived space.

This suggests that enhanced spaciousness occurs when we see more, when we are near the walls or corners of a room (where variance increases); and when we see less of an enclosing perimeter, and when that enclosing perimeter is not a highly irregular one that cuts off interior views.

The portion of these results which deal exclusively with perimeter might at first seem to conflict with earlier findings that less compact spaces (i.e., having more perimeter for a given area) are judged as more voluminous than compact ones. Benedikt and Burnham (1985), however, describe a subsequent test comparing a rectangular and square room, which determined that the square room did not seem larger than the rectangular one. It appears that the perimeter effect observed by these researchers resulted from the way in which model rooms were constructed, which often resulted in "histogram" type configurations that produced long corridor-like appendages highly dissimilar to real environments. Otherwise, their results provide strong confirmation of the earlier studies, and show that isovist theory is capable of capturing those aspects of visible space that seem most involved with perceived spaciousness.

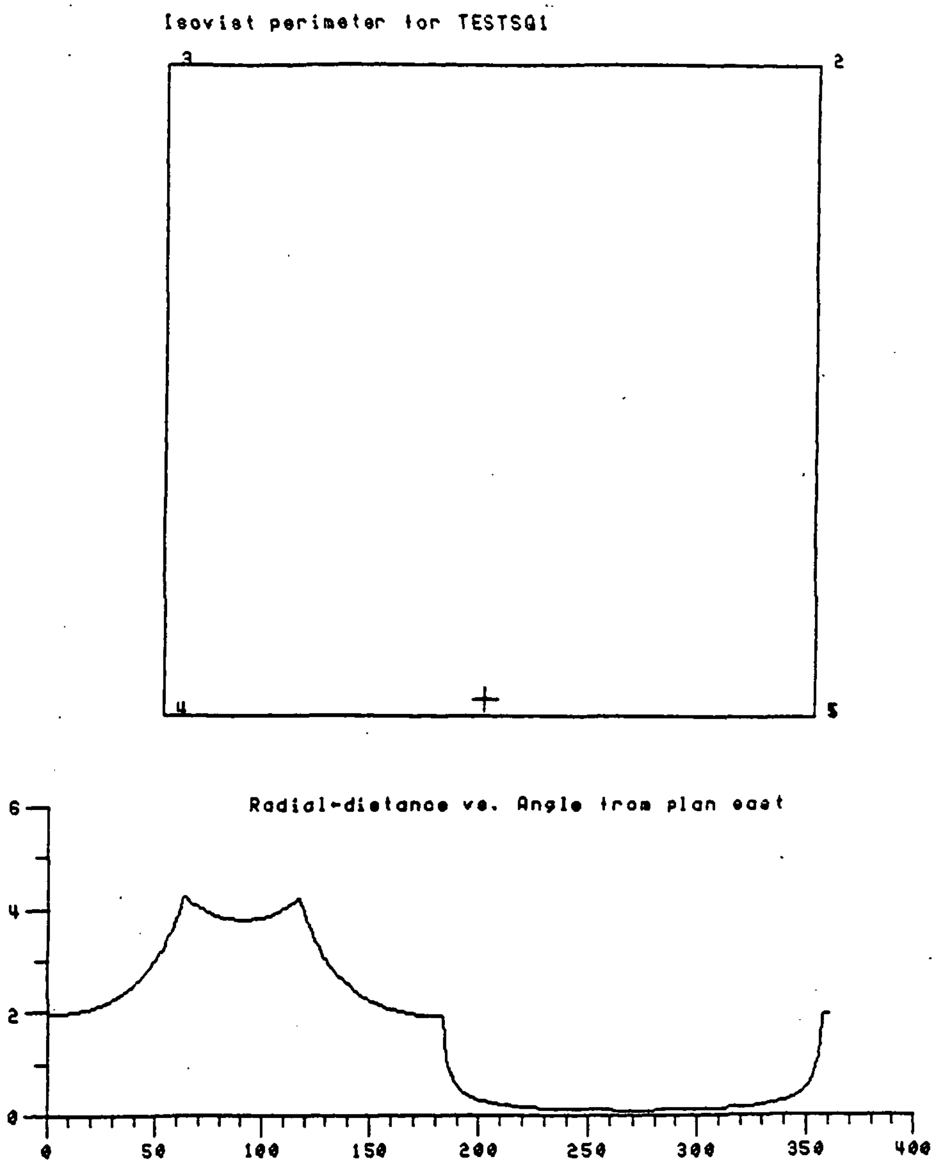
In order to investigate more thoroughly the relationship between isovists and the compactness of rooms, we simulated views from different positions within rectangular and square enclosures. The results of these exercises are shown here in figures 18 through 26. They can be compared with the isovists within a parallelogram-type of cabin in figures 27 through 29.

Insert Figures 18 thru 29

These again confirm the results of past empirical studies, if those are reinterpreted in terms of isovist theory. From comparable viewpoints, the isovist in a rectangular space always has a greater variance than the isovist in a square space. The lambda measure of sequential variability shows no such clear dominance, indicating that it is sensitive to a different type of spatial complexity than the variance of the isovist. Variance is driven by long axial views. Lambda is driven by rapid, large changes in successive isovist radials. Previous studies have neither conceived nor tested this particular kind of spatial variability, although it would seem to be very pertinent to the designers' heuristics that "to enhance spaciousness, the eye should move smoothly over a room."

If this dictum is to be believed, then low values of lambda should be associated with higher sensed spaciousness. This would make its effect inverse to that of increasing variance for the same purpose. Compare, for example, the effect on lambda of moving into a corner vs. the middle of a square or rectangular room. In a square enclosure lambda proportionally decreases to a greater degree.

For our purposes at the moment, it is noteworthy that it is possible to describe two very different measures of spatial complexity that allow



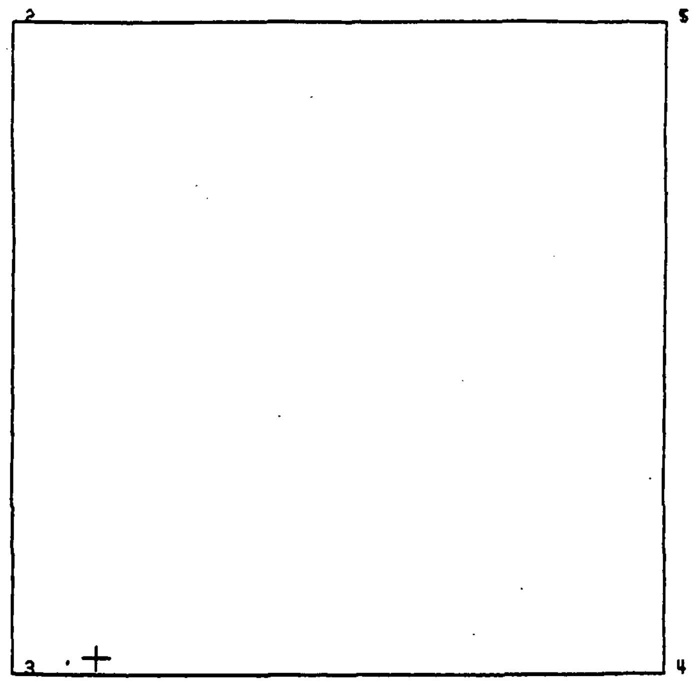
ISOVIST file TESTSQ1

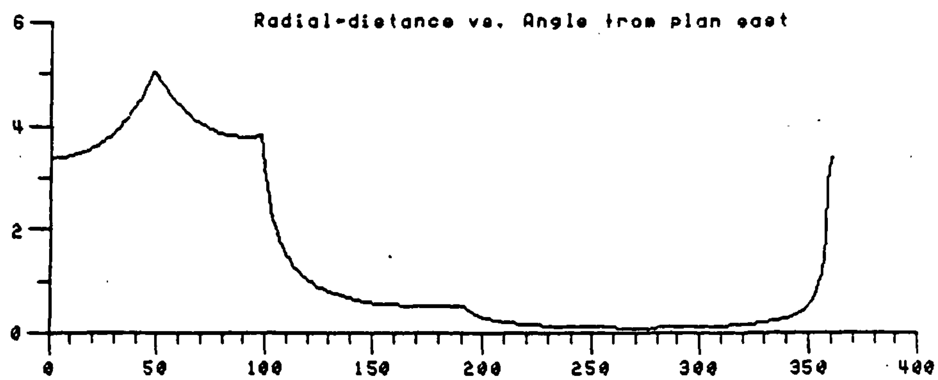
Isovist Area (A) =	15.054
Total Perimeter (T) =	15.520
Occlusive perimeter(Q)=	0.000
Visible Perimeter (P) =	15.520
R-min =	0.100
R-max =	4.242
R-mean =	1.819
Standard Deviation =	1.474
Variance (M2) =	2.172
Skewness (M3) =	1.198

Un-rotated position.

Variability (lamda) =	0.948
Compactness (C) =	16.000
Circularity (N) =	1.273
Q/P =	0.000
Q/T =	0.000
M2/A =	0.144
M3/A =	0.080

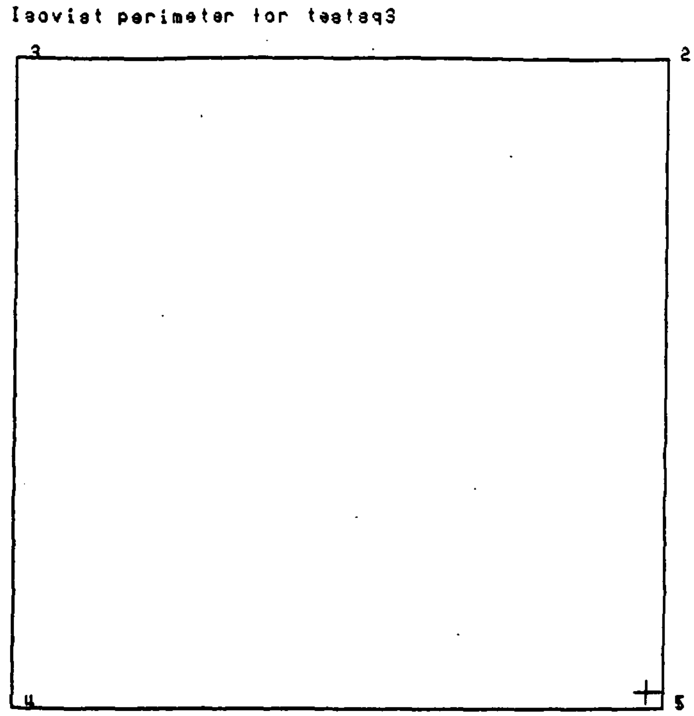
Figure 18

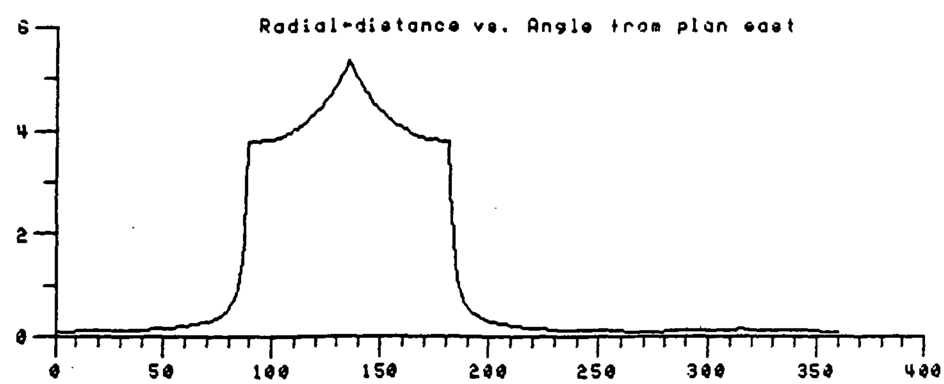




ISOVIST file TESTSQ2		Un-rotated position.	
Isovist Area (A) =	15.054	Variability (lamda) =	1.174
Total Perimeter (T) =,	15.520	Compactness (C) =	16.000
Occlusive perimeter(Q)=	0.000	Circularity (N) =	1.273
Visible Perimeter (P) =	15.520	Q/P =	0.000
R-min =	0.100	Q/T =	0.000
R-max =	5.051	M2/A =	0.182
R-mean =	1.433	M3/A =	0.268
Standard Deviation =	1.654		
Variance (M2) =	2.737		
Skewness (M3) =	4.030		

Figure 19

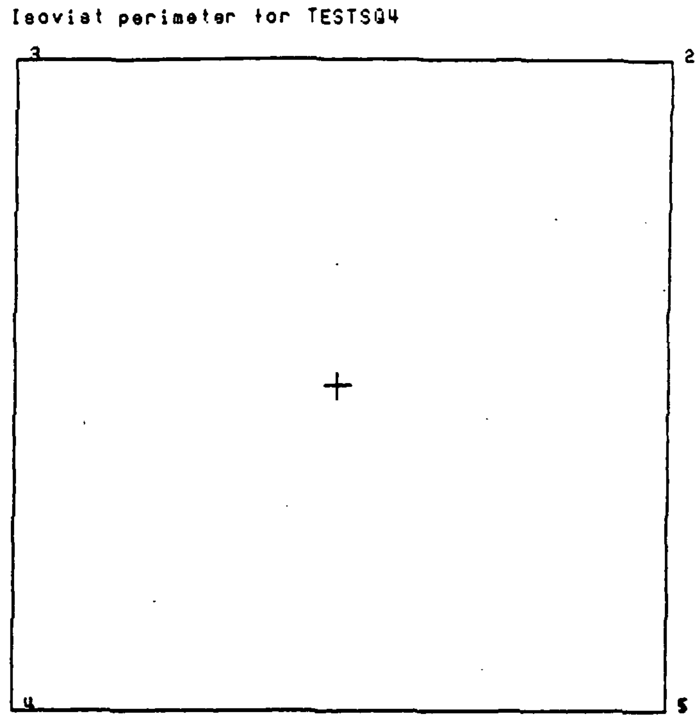


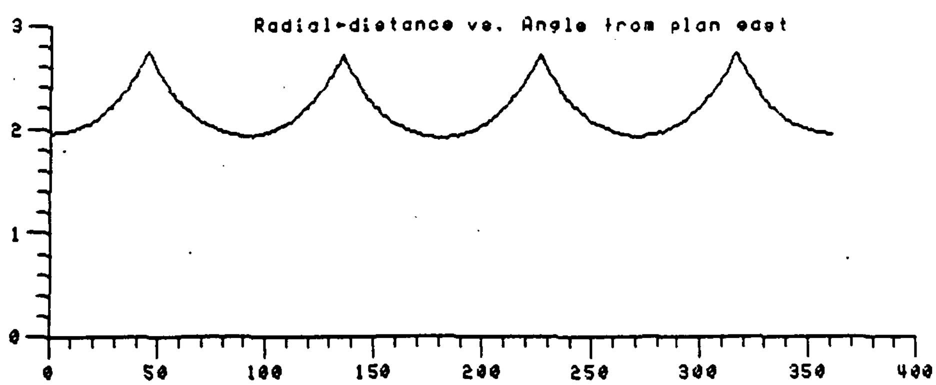


ISOVIST file testsq3	
Isovist Area (A) =	15.054
Total Perimeter (T) =	15.520
Occlusive perimeter(Q) =	0.000
Visible Perimeter (P) =	15.520
R-min =	0.100
R-max =	5.346
R-mean =	1.258
Standard Deviation =	1.791
Variance (M2) =	3.207
Skewness (M3) =	6.311

Un-rotated position.	
Variability (lamda) =	0.804
Compactness (C) =	16.000
Circularity (N) =	1.273
Q/P =	0.000
Q/T =	0.000
M2/A =	0.213
M3/A =	0.419

Figure 20





ISOVIST file TESTSQ4

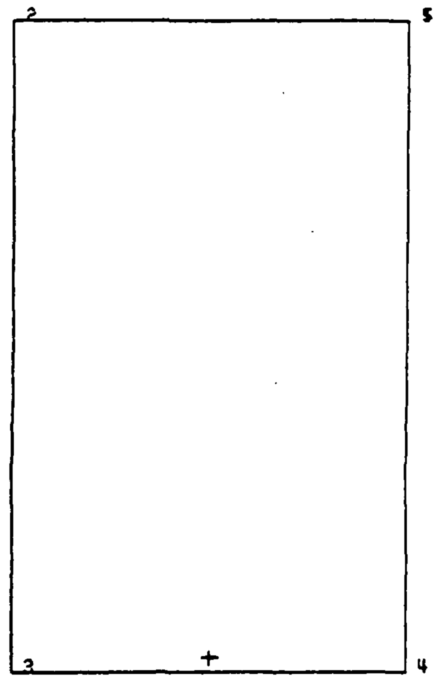
Isovist Area (A) =	15.054
Total Perimeter (T) =	15.520
Occlusive perimeter(Q)=	0.000
Visible Perimeter (P) =	15.520
R-min =	1.920
R-max =	2.744
R-mean =	2.177
Standard Deviation =	0.229
Variance (M2) =	0.053
Skewness (M3) =	0.010

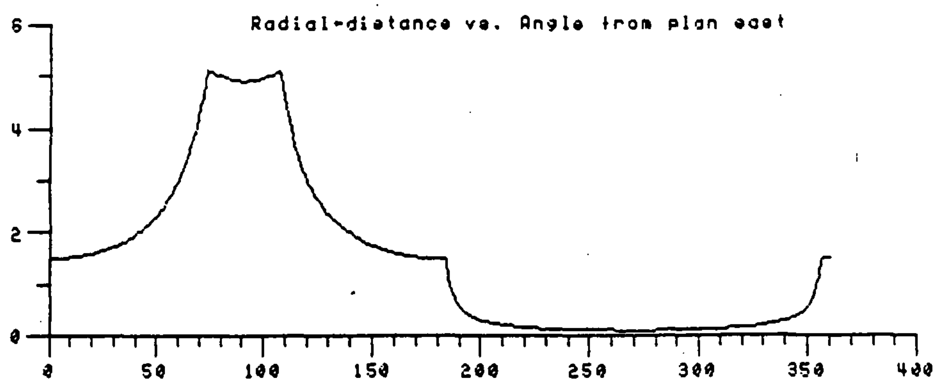
Un-rotated position.

Variability (lamda) =	0.984
Compactness (C) =	16.000
Circularity (N) =	1.273
Q/P =	0.000
Q/T =	0.000
M2/A =	0.003
M3/A =	0.001

Figure 21

Isovist perimeter for testrecl





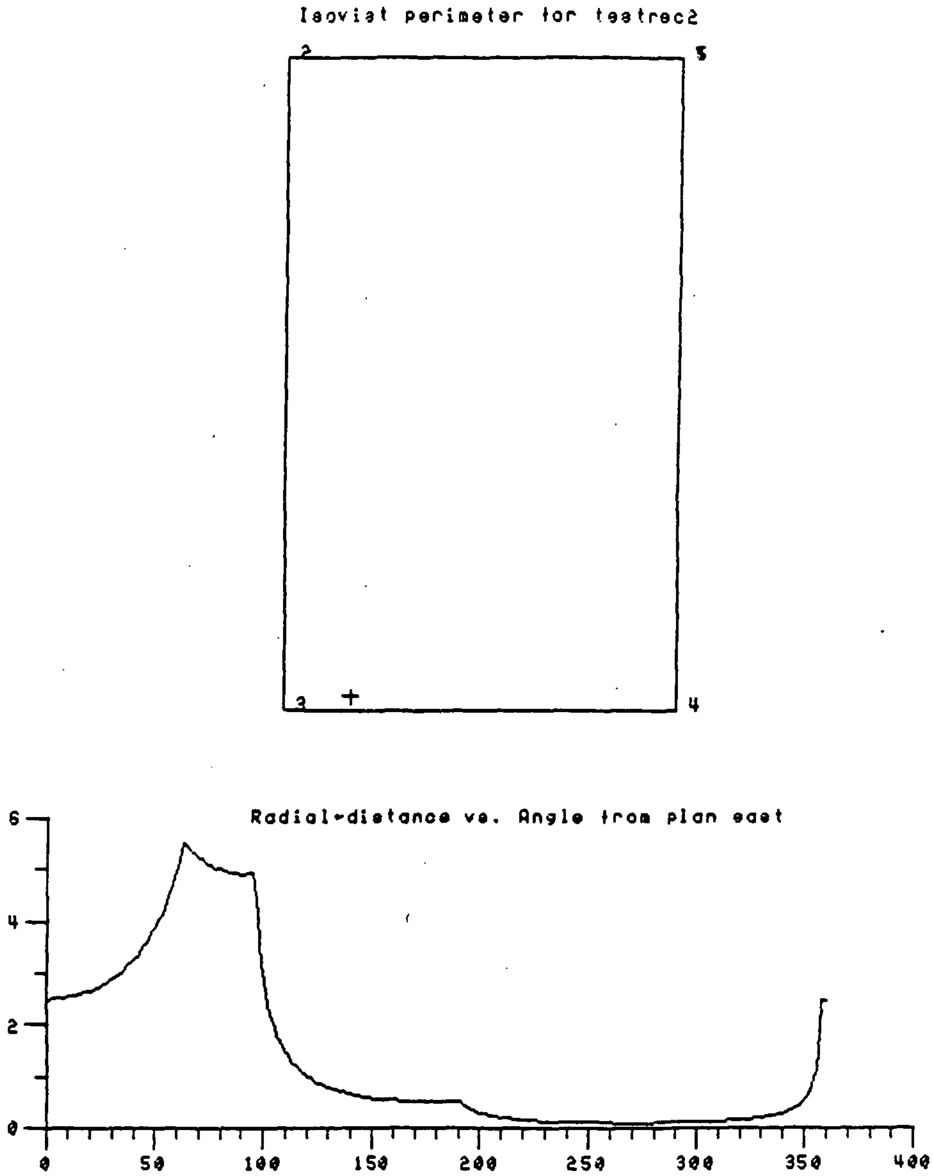
ISOVIST file testrecl
BME file testrecl

Isovist Area (A) =	15.000
Total Perimeter (T) =	16.000
Occlusive perimeter(Q) =	0.000
Visible Perimeter (P) =	16.000
R-min =	0.100
R-max =	5.124
R-mean =	1.518
Standard Deviation =	1.573
Variance (M2) =	2.473
Skewness (M3) =	4.020

Un-rotated position.

Variability (lamda) =	0.887
Compactness (C) =	17.067
Circularity (N) =	1.358
Q/P =	0.000
Q/T =	0.000
M2/A =	0.165
M3/A =	0.268

Figure 22



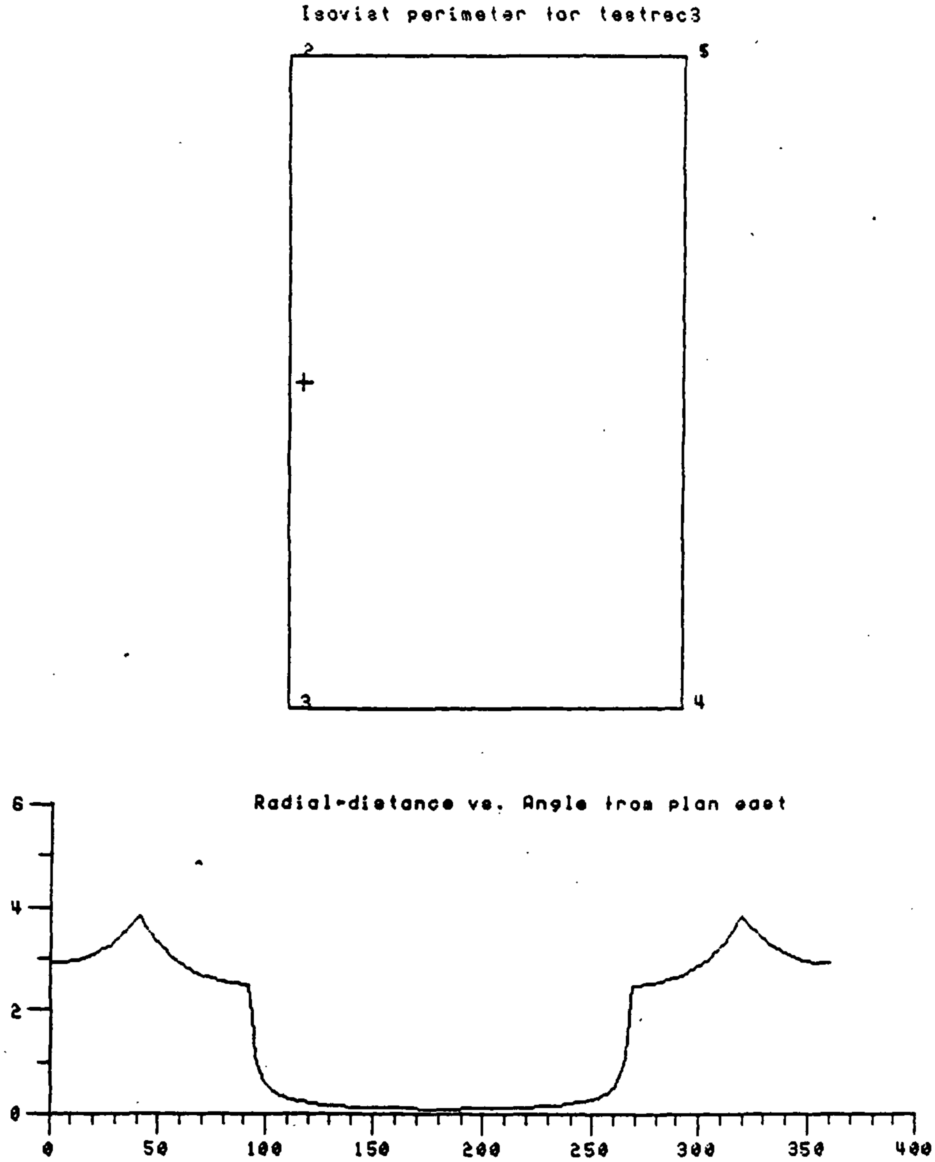
ISOVIST file testrec2

Isovist Area (A) =	15.000
Total Perimeter (T) =	16.000
Occlusive perimeter(Q)=	0.000
Visible Perimeter (P) =	16.000
R-min =	0.100
R-max =	5.499
R-mean =	1.397
Standard Deviation =	1.680
Variance (M2) =	2.824
Skewness (M3) =	5.593

Un-rotated position.

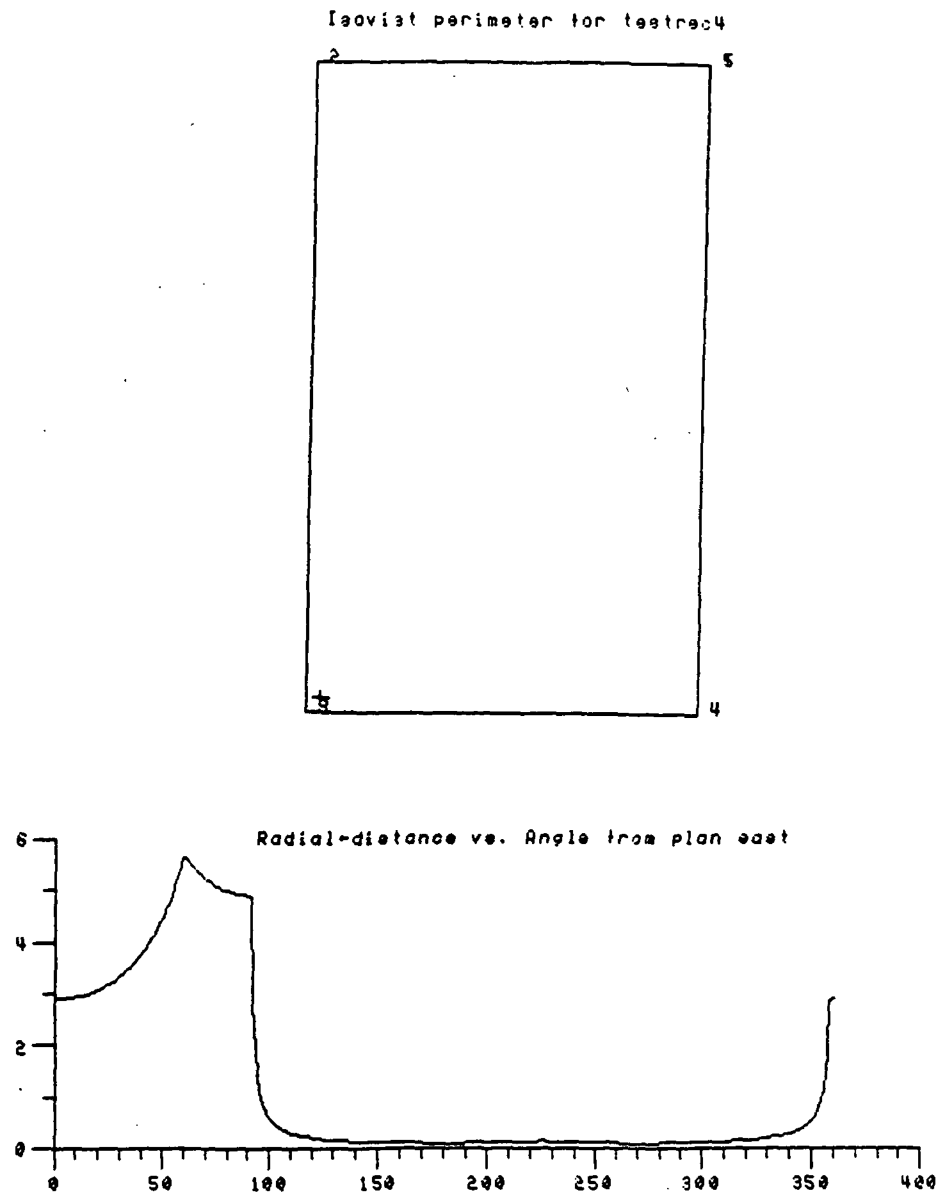
Variability (lamda) =	1.052
Compactness (C) =	17.067
Circularity (N) =	1.358
Q/P =	0.000
Q/T =	0.000
M2/A =	0.188
M3/A =	0.373

Figure 23



ISOVIST file testrec3		Un-rotated position.	
Isovist Area (A) =	15.000	Variability (lamda) =	1.011
Total Perimeter (T) =	16.000	Compactness (C) =	17.067
Occlusive perimeter(Q)=	0.000	Circularity (N) =	1.358
Visible Perimeter (P) =	16.000	Q/P =	0.000
R-min =	0.100	Q/T =	0.000
R-max =	3.811	M2/A =	0.134
R-mean =	1.865	M3/A =	0.001
Standard Deviation =	1.415		
Variance (M2) =	2.004		
Skewness (M3) =	0.008		

Figure 24



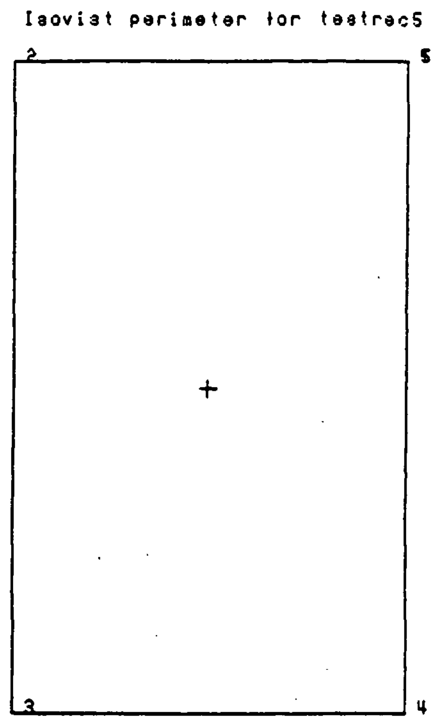
ISOVIST file testrec4

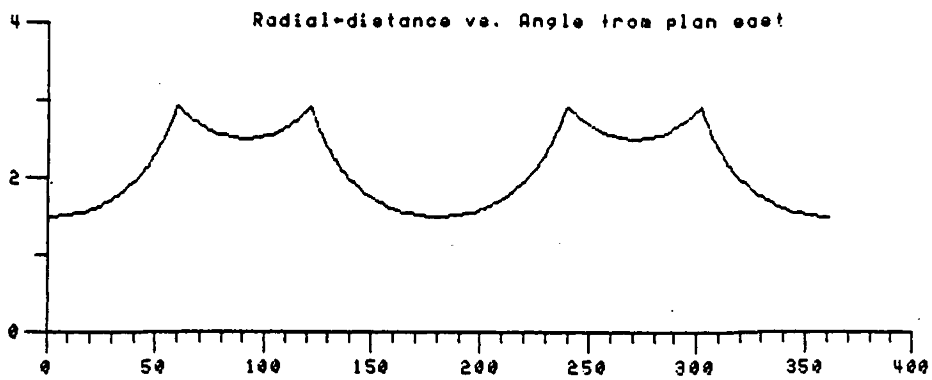
Isovist Area (A) =	15.000
Total Perimeter (T) =	16.000
Occlusive perimeter(Q)=	0.000
Visible Perimeter (P) =	16.000
R-min =	0.100
R-max =	5.658
R-mean =	1.234
Standard Deviation =	1.804
Variance (M2) =	3.256
Skewness (M3) =	7.520

Un-rotated position.

Variability (lamda) =	1.131
Compactness (C) =	17.067
Circularity (N) =	1.358
Q/P =	0.000
Q/T =	0.000
M2/A =	0.217
M3/A =	0.501

Figure 25





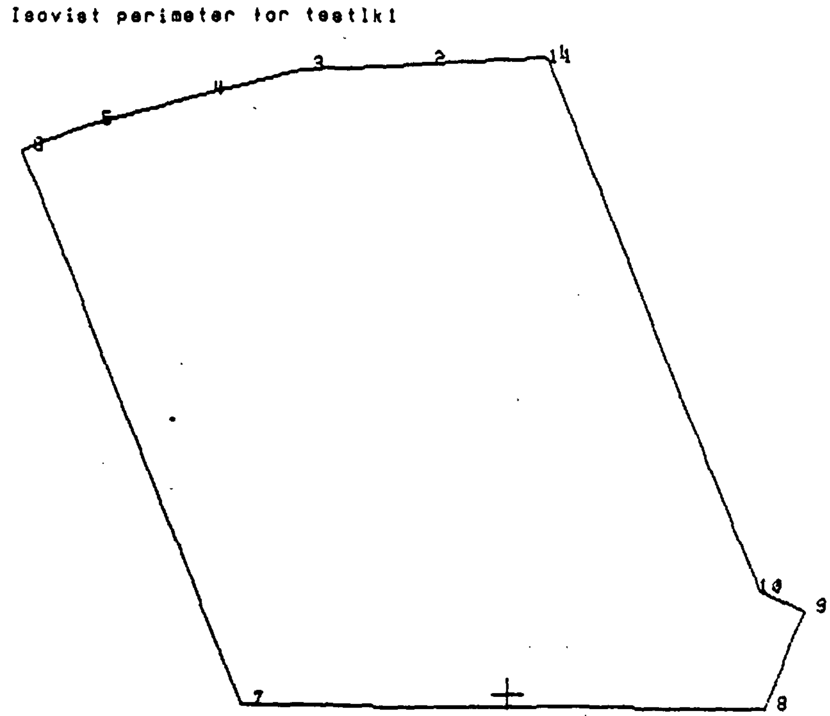
ISOVIST file testrec5

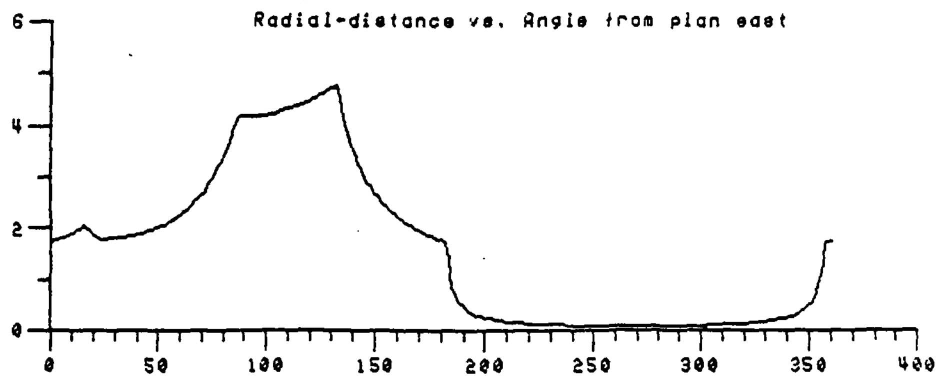
Isovist Area (A) =	15.000
Total Perimeter (T) =	16.000
Occlusive perimeter(Q)=	0.000
Visible Perimeter (P) =	16.000
R-min =	1.500
R-max =	2.912
R-mean =	2.131
Standard Deviation =	0.482
Variance (M2) =	0.233
Skewness (M3) =	0.002

Un-rotated position.

Variability (lamda) =	1.143
Compactness (C) =	17.067
Circularity (N) =	1.353
Q/P =	0.000
Q/T =	0.000
M2/A =	0.016
M3/A =	0.000

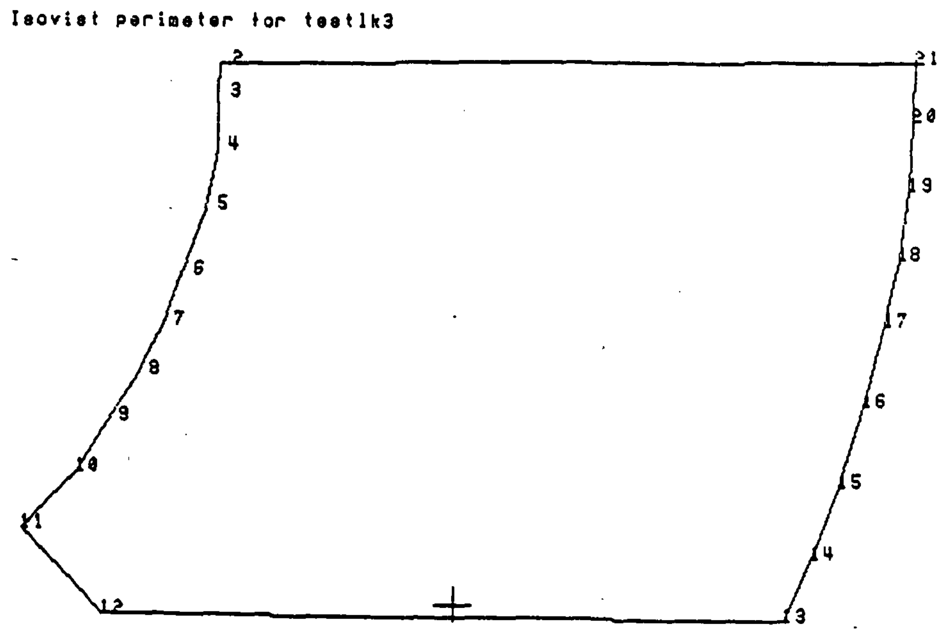
Figure 26

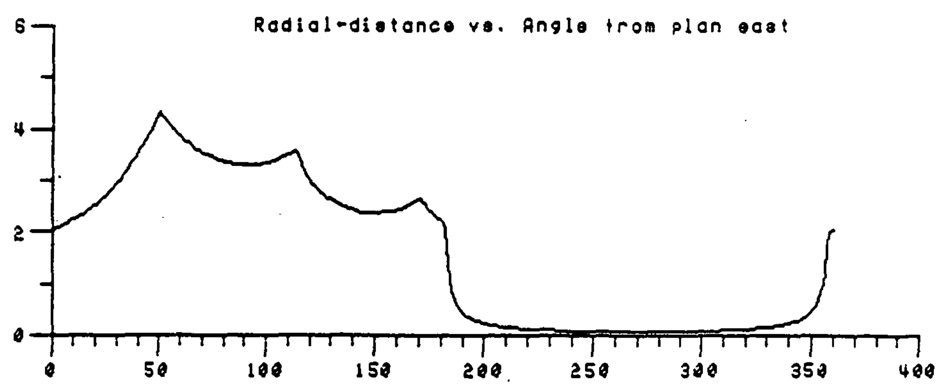




ISOVIST file testlk1		Un-rotated position.	
Isovist Area (A) =	15.088	Variability (lamda) =	0.928
Total Perimeter (T) =	15.694	Compactness (C) =	16.324
Occlusive perimeter(Q) =	0.000	Circularity (N) =	1.299
Visible Perimeter (P) =	15.694	Q/P =	0.000
R-min =	0.085	Q/T =	0.000
R-max =	4.779	M2/A =	0.155
R-mean =	1.569	M3/A =	0.152
Standard Deviation =	1.530		
Variance (M2) =	2.341		
Skewness (M3) =	2.298		

Figure 27



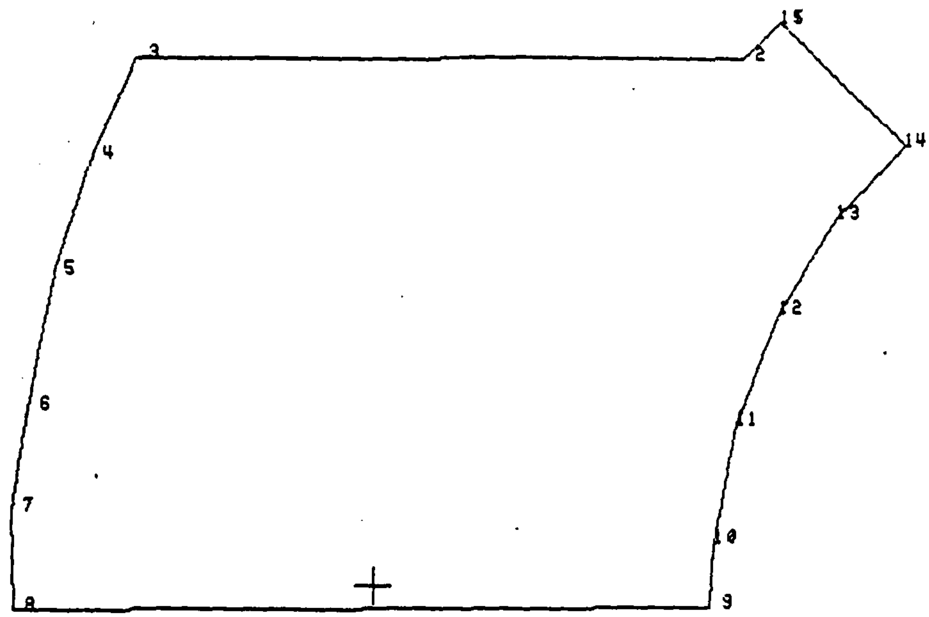


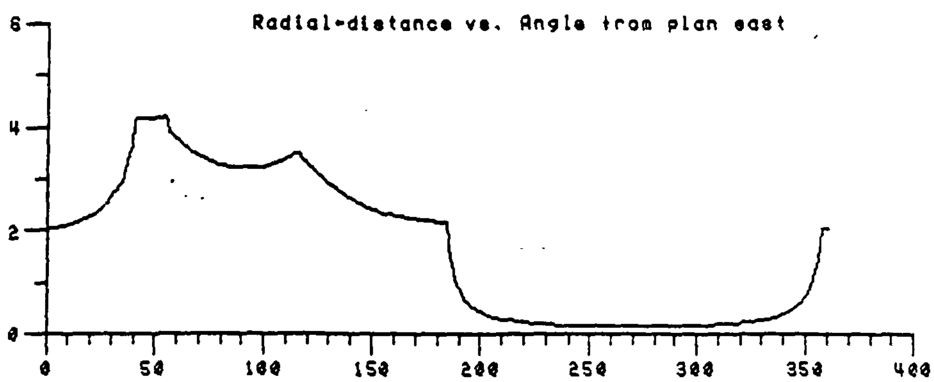
ISOVIST file testlk3	
Isovist Area (A) =	15.007
Total Perimeter (T) =	15.781
Occlusive perimeter(Q)=	0.000
Visible Perimeter (P) =	15.781
R-min =	0.080
R-max =	4.325
R-mean =	1.626
Standard Deviation =	1.460
Variance (M2) =	2.132
Skewness (M3) =	0.527

Un-rotated position.	
Variability (lamda) =	0.973
Compactness (C) =	16.595
Circularity (N) =	1.321
Q/P =	0.000
Q/T =	0.000
M2/A =	0.142
M3/A =	0.035

Figure 28

Isovist perimeter for testlk4





ISOVIST file testlk4		Un-rotated position.	
Isovist Area (A) =	15.011	Variability (lamda) =	0.959
Total Perimeter (T) =	15.919	Compactness (C) =	16.883
Occlusive perimeter(Q)=	0.000	Circularity (N) =	1.343
Visible Perimeter (P) =	15.919	Q/P =	0.000
R-min =	0.139	Q/T =	0.000
R-max =	4.217	M2/A =	0.131
R-mean =	1.677	M3/A =	0.035
Standard Deviation =	1.402		
Variance (M2) =	1.965		
Skewness (M3) =	0.519		

Figure 29

operationalizing different qualitative design heuristics. Variance (and compactness) deal with how spaces elongate or open into each other, while lambda deals with the smoothness of an enclosure. There is a rich opportunity here for future empirical investigation.

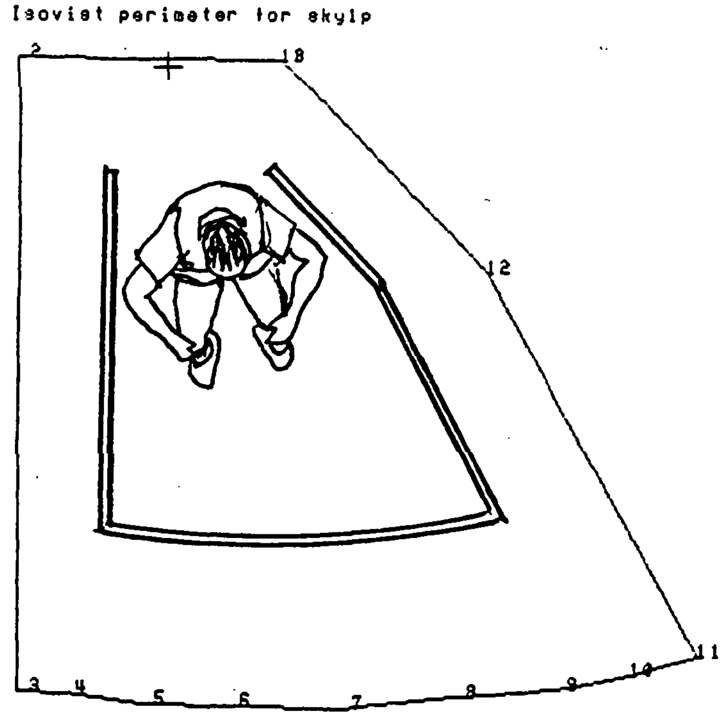
Given the apparent efficacy of isovist measures, we constructed simulations of isovists for different proposed and precedent (Skylab) private crew quarters. Figures 30 through 44 present these results.

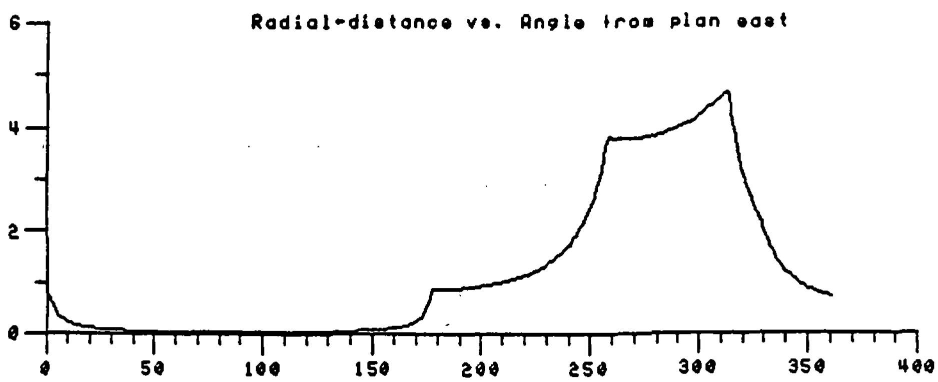
Insert Figures 30 thru 44

Inspection of the graphs and tables shows that there are considerable differences in the (apparently) most important isovist measures. The area of the isovist, taken from the entryway or a proposed sleepsack position, varies over a multiple of 2.5 from smallest to largest.

Because areas are not equal, a proper comparison of variability among these spaces is the coefficient of variation, not the variance, per se. This is the variance divided by the area, symbolized by M_2/A in the tables. Note, how, in the more irregular and less compact spaces M_2/A is higher with comparable viewing positions within a compartment. It seems that this should be a desired feature if a small space is to be seen as more interesting, varied, and spacious, given empirical studies as a guide.

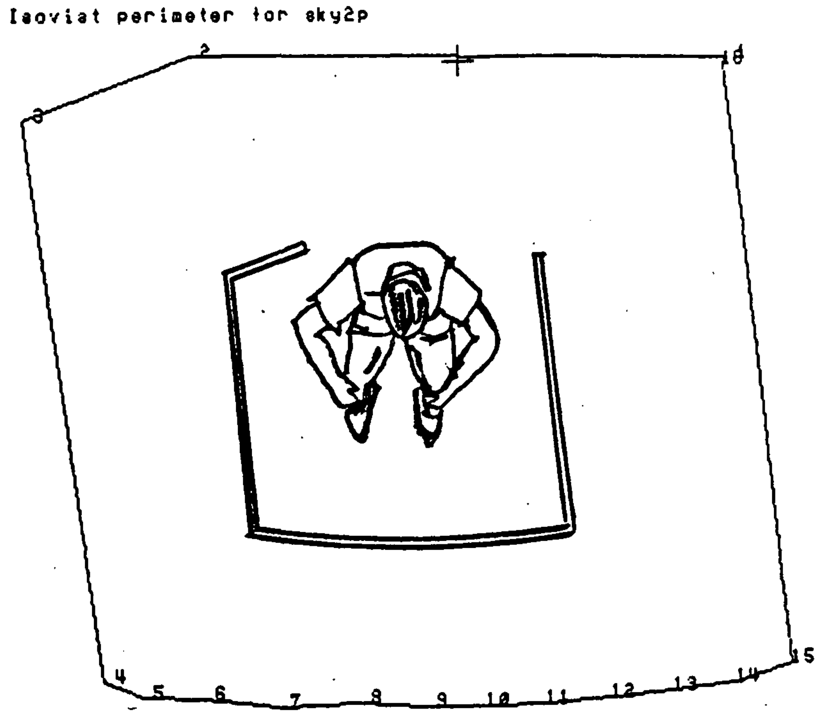
The results from the Skylab sleep compartments permit a postdiction of which compartments should have been regarded as most spacious by the different crews. If isovist measures can be retroactively applied here, we

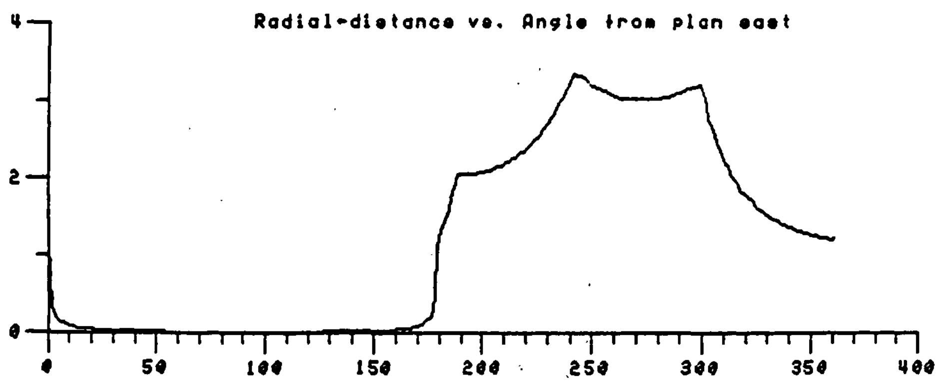




ISOVIST file skylp		Un-rotated position.	
Isovist Area (A) =	11.433	Variability (lamda) =	0.874
Total Perimeter (T) =	13.719	Compactness (C) =	16.462
Occlusive perimeter(Q)=	0.020	Circularity (N) =	1.310
Visible Perimeter (P) =	13.699	Q/P =	0.001
R-min =	0.039	Q/T =	0.001
R-max =	4.675	M2/A =	0.188
R-mean =	1.217	M3/A =	0.299
Standard Deviation =	1.464		
Variance (M2) =	2.145		
Skewness (M3) =	3.418		

Figure 30





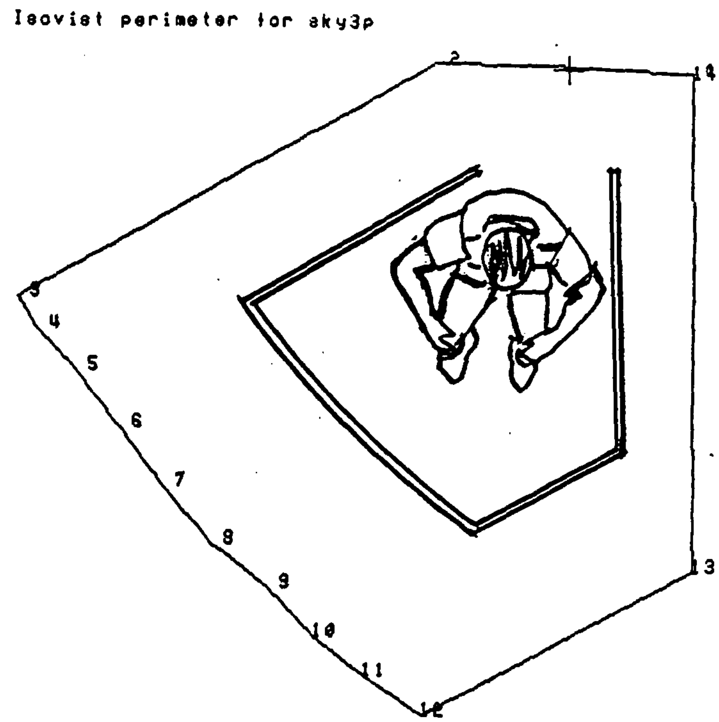
ISOVIST file sky2p

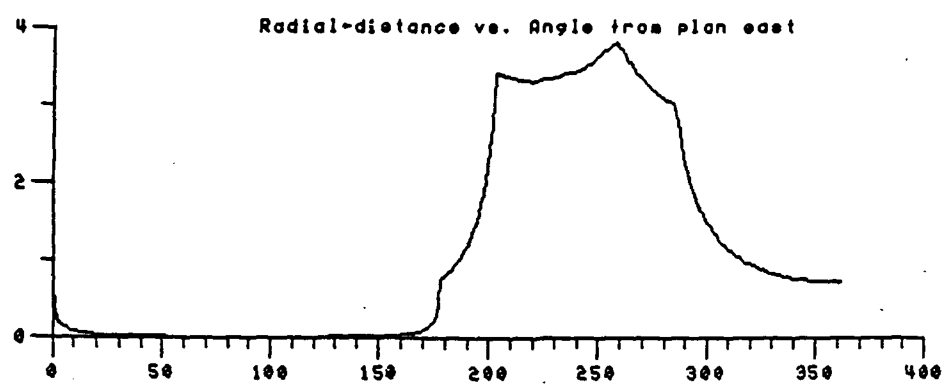
Isovist Area (A) =	9.546
Total Perimeter (T) =	12.027
Occlusive perimeter(Q)=	0.000
Visible Perimeter (P) =	12.027
R-min =	0.015
R-max =	3.323
R-mean =	1.210
Standard Deviation =	1.255
Variance (M2) =	1.575
Skewness (M3) =	0.761

Un-rotated position.

Variability (lamda) =	0.965
Compactness (C) =	15.152
Circularity (N) =	1.206
Q/P =	0.000
Q/T =	0.000
M2/A =	0.165
M3/A =	0.080

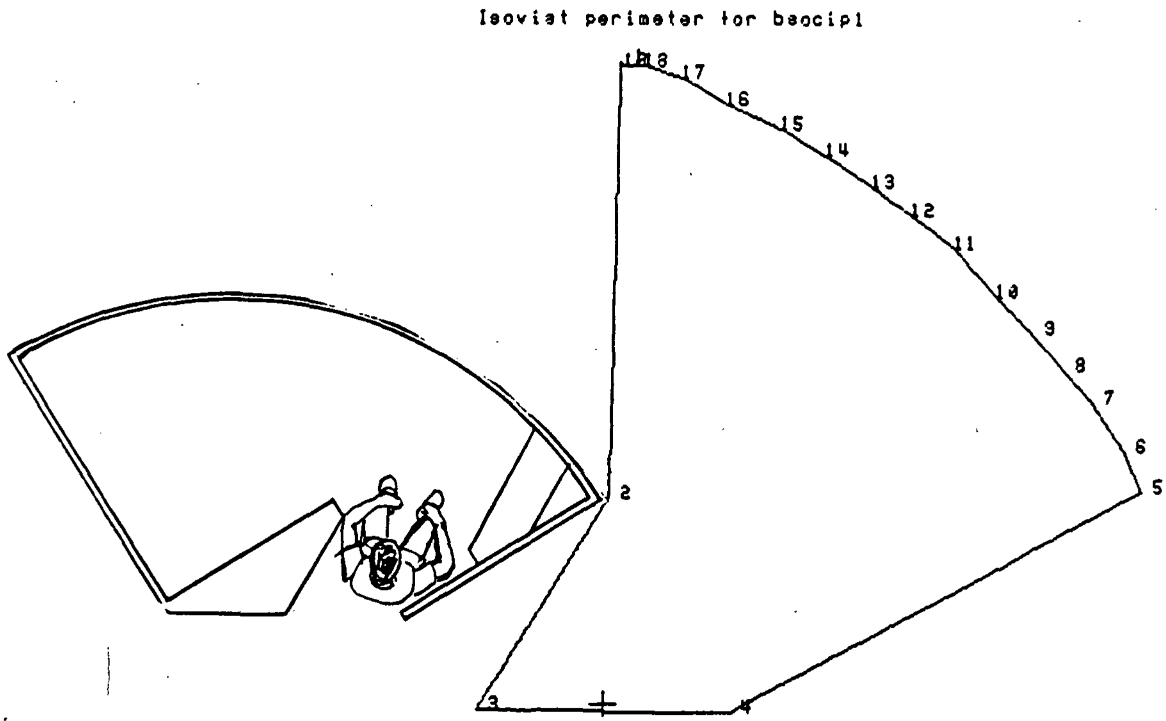
Figure 31

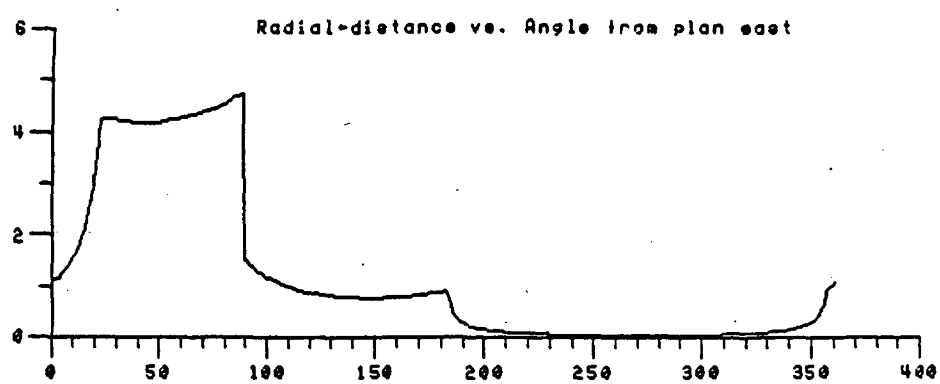




ISOVIST file sky3p		Un-rotated position.	
Isovist Area (A) =	9.837	Variability (lamda) =	0.896
Total Perimeter (T) =	12.269	Compactness (C) =	15.302
Occlusive perimeter(Q) =	0.000	Circularity (N) =	1.218
Visible Perimeter (P) =	12.269	Q/P =	0.000
R-min =	0.015	Q/T =	0.000
R-max =	3.803	M2/A =	0.188
R-mean =	1.130	M3/A =	0.218
Variance (M2) =	1.846		
Skewness (M3) =	2.145		

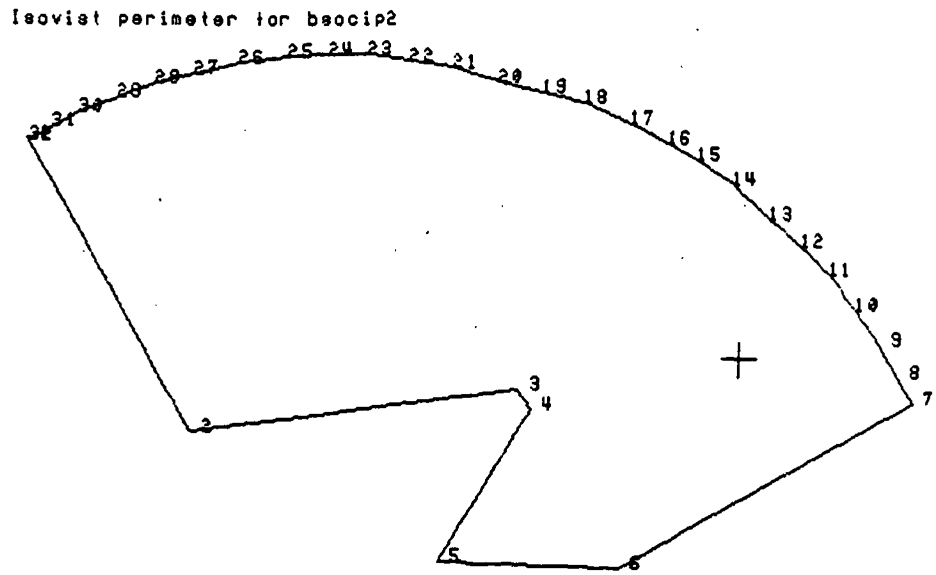
Figure 32

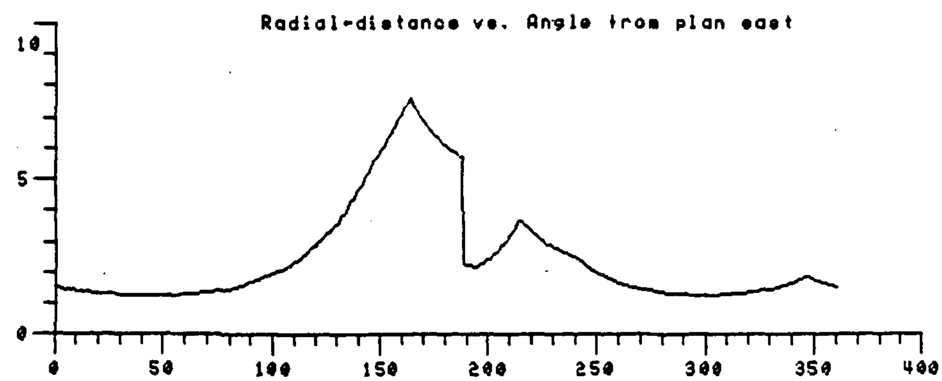




ISOVIST file bsocipl		Un-rotated position.	
Isovist Area (A) =	12.616	Variability (lamda) =	0.965
Total Perimeter (T) =	15.525	Compactness (C) =	19.106
Occlusive perimeter(Q)=	3.240	Circularity (N) =	1.520
Visible Perimeter (P) =	12.285	Q/P =	0.264
R-min =	0.050	Q/T =	0.209
R-max =	4.747	M2/A =	0.198
R-mean =	1.224	M3/A =	0.403
Standard Deviation =	1.582		
Variance (M2) =	2.502		
Skewness (M3) =	5.085		

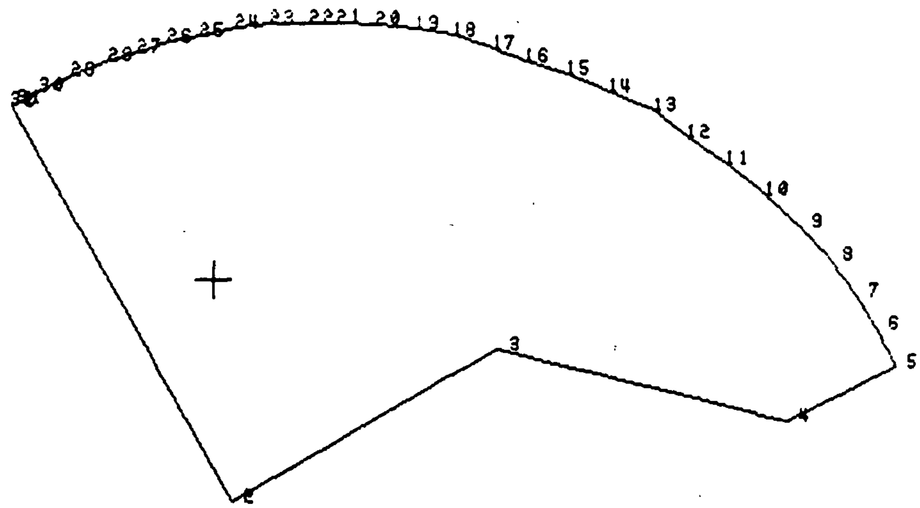
Figure 33

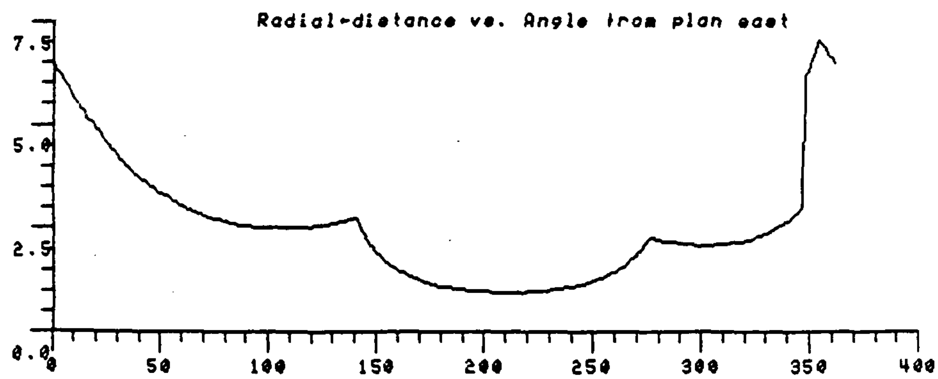




ISOVIST file bsocip2		Un-rotated position.	
Isovist Area (A) =	28.270	Variability (lamda) =	0.833
Total Perimeter (T) =	24.785	Compactness (C) =	21.729
Occlusive perimeter(Q)=	3.390	Circularity (N) =	1.729
Visible Perimeter (P) =	21.395	Q/P =	0.158
R-min =	1.251	Q/T =	0.137
R-max =	7.606	M2/A =	0.099
R-mean =	2.486	M3/A =	0.272
Standard Deviation =	1.677		
Variance (M2) =	2.813		
Skewness (M3) =	7.685		

Figure 34





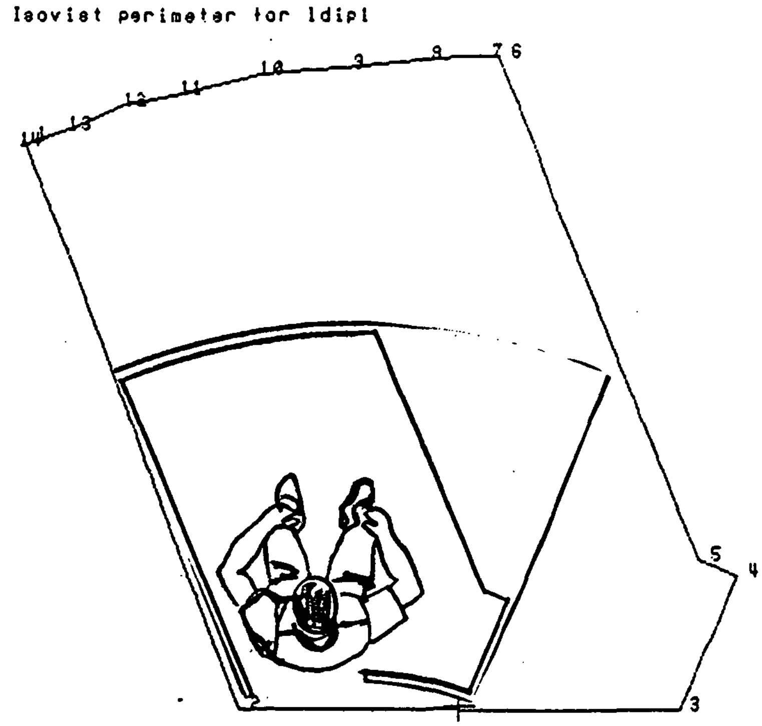
ISOVIST file baocip3

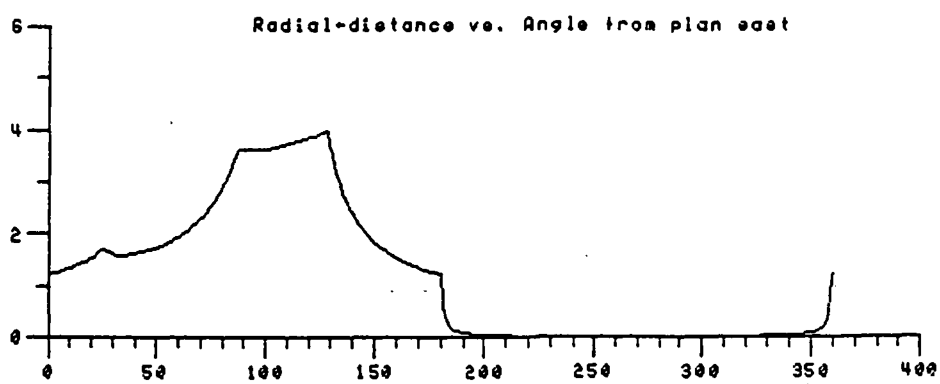
Isovist Area (A) =	26.371
Total Perimeter (T) =	22.710
Occlusive perimeter(Q)=	3.068
Visible Perimeter (P) =	19.642
R-min =	0.947
R-max =	7.052
R-mean =	2.511
Standard Deviation =	1.438
Variance (M2) =	2.067
Skewness (M3) =	4.099

Un-rotated position.

Variability (lamda) =	1.409
Compactness (C) =	19.558
Circularity (N) =	1.556
Q/P =	0.156
Q/T =	0.135
M2/A =	0.078
M3/A =	0.155

Figure 35

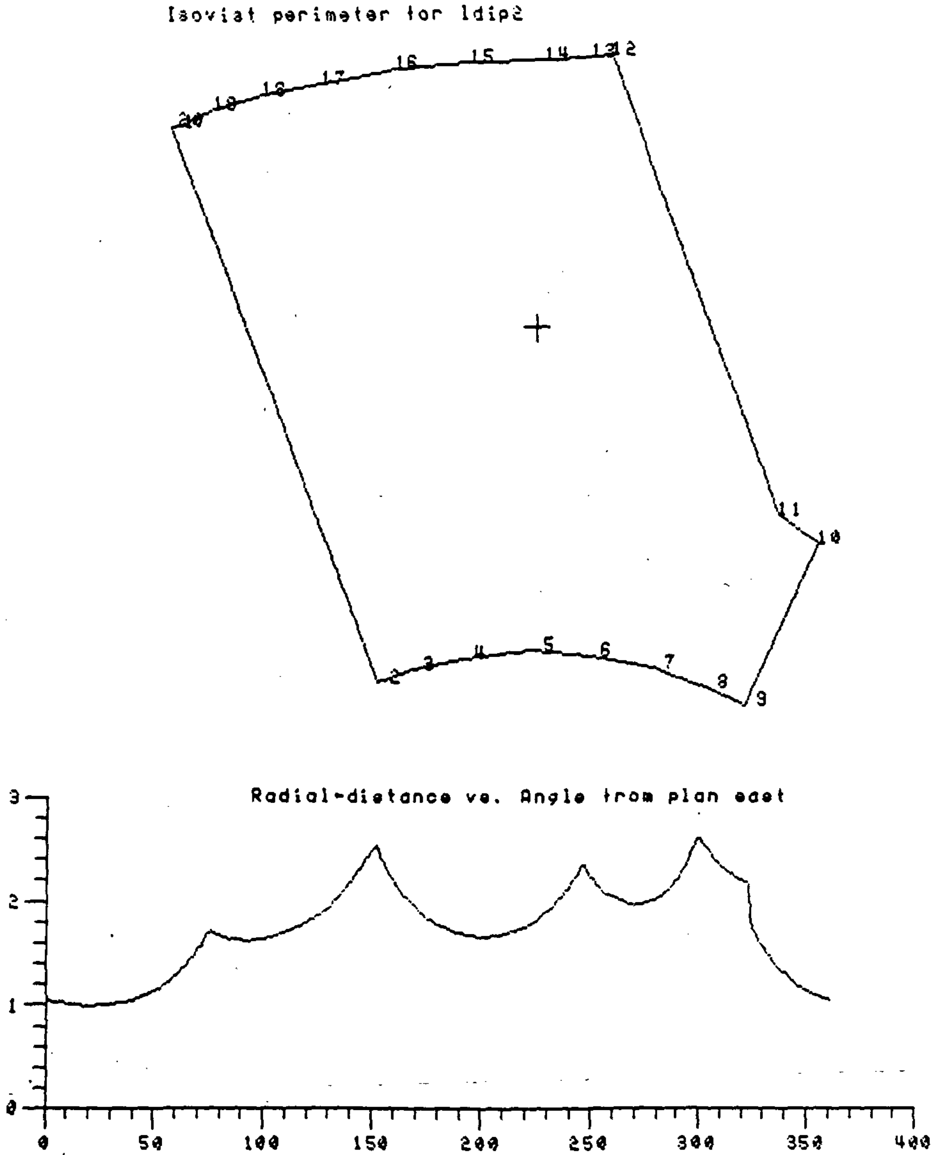




ISOVIST file ldipl	
Isovist Area (A) =	9.300
Total Perimeter (T) =	12.720
Occlusive perimeter(Q) =	0.000
Visible Perimeter (P) =	12.720
R-min =	0.015
R-max =	3.987
R-mean =	1.192
Standard Deviation =	1.316
Variance (M2) =	1.733
Skewness (M3) =	1.693

Un-rotated position.	
Variability (lamda) =	0.923
Compactness (C) =	16.342
Circularity (N) =	1.300
Q/P =	0.000
Q/T =	0.000
M2/A =	0.175
M3/A =	0.171

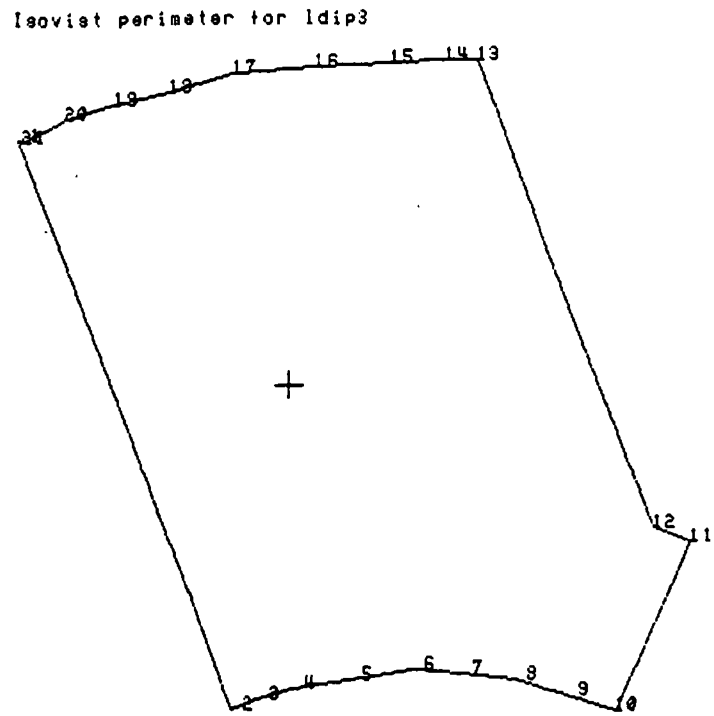
Figure 36

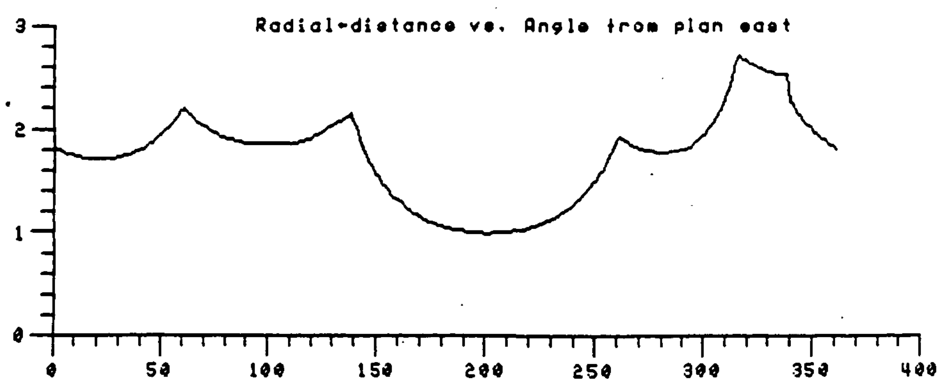


ISOVIST file ldip2	
Isovist Area (A) =	10.058
Total Perimeter (T) =	13.027
Occlusive perimeter(Q)=	0.294
Visible Perimeter (P) =	12.733
R-min =	0.991
R-max =	2.607
R-mean =	1.735
Standard Deviation =	0.439
Variance (M2) =	0.193
Skewness (M3) =	-0.016

Un-rotated position.	
Variability (lamda) =	1.284
Compactness (C) =	16.872
Circularity (N) =	1.343
Q/P =	0.023
Q/T =	0.023
M2/A =	0.019
M3/A =	-0.002

Figure 37

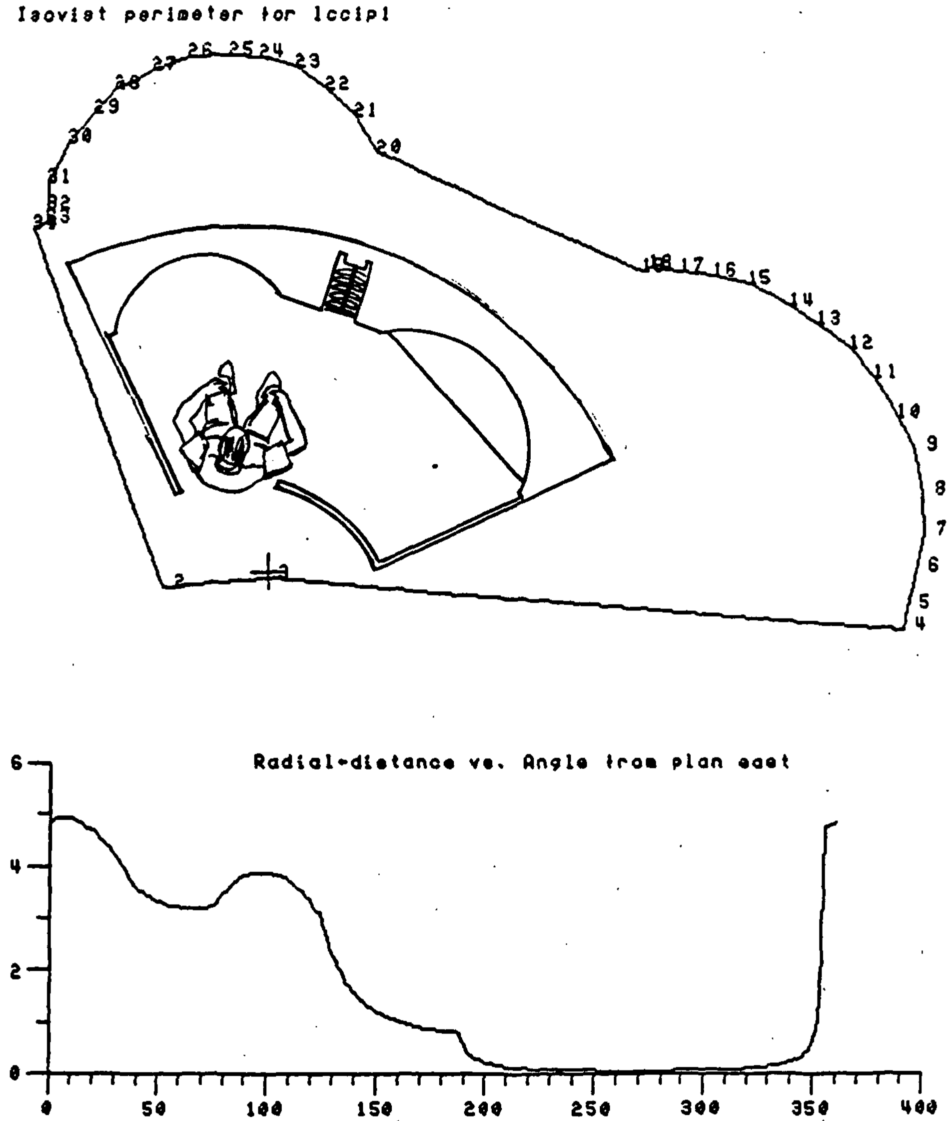




ISOVIST file ldip3	
Isovist Area (A) =	10.134
Total Perimeter (T) =	12.982
Occlusive perimeter(Q)=	0.242
Visible Perimeter (P) =	12.740
R-min =	0.992
R-max =	2.724
R-mean =	1.742
Standard Deviation =	0.436
Variance (M2) =	0.190
Skewness (M3) =	-0.011

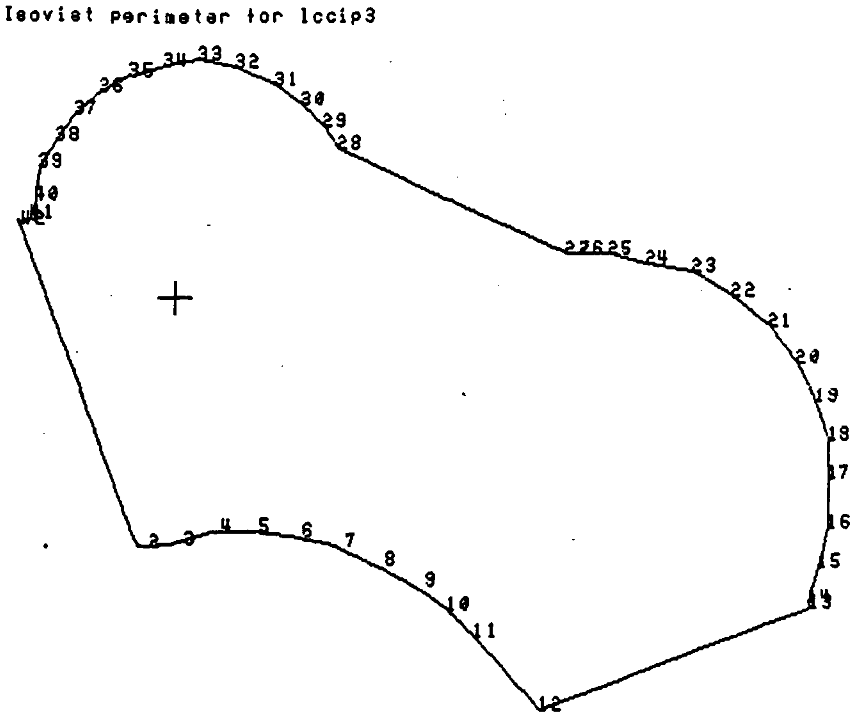
Un-rotated position.	
Variability (lamda) =	0.884
Compactness (C) =	16.630
Circularity (N) =	1.323
Q/P =	0.019
Q/T =	0.019
M2/A =	0.019
M3/A =	-0.001

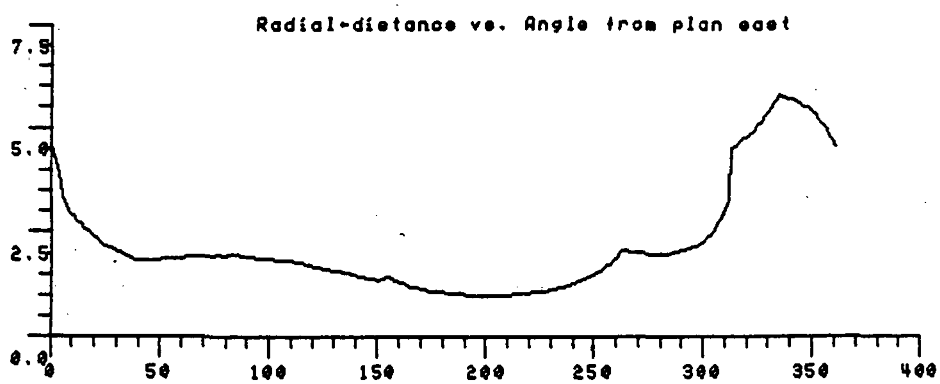
Figure 38



ISOVIST file lccipl		Un-rotated position.	
Isovist Area (A) =	18.483	Variability (lamda) =	1.311
Total Perimeter (T) =	18.111	Compactness (C) =	17.746
Occlusive perimeter(Q)=	0.000	Circularity (N) =	1.412
Visible Perimeter (P) =	18.111	Q/P =	0.000
R-min =	0.061	Q/T =	0.000
R-max =	4.912	M2/A =	0.163
R-mean =	1.695	M3/A =	0.147
Standard Deviation =	1.734		
Variance (M2) =	3.005		
Skewness (M3) =	2.726		

Figure 39

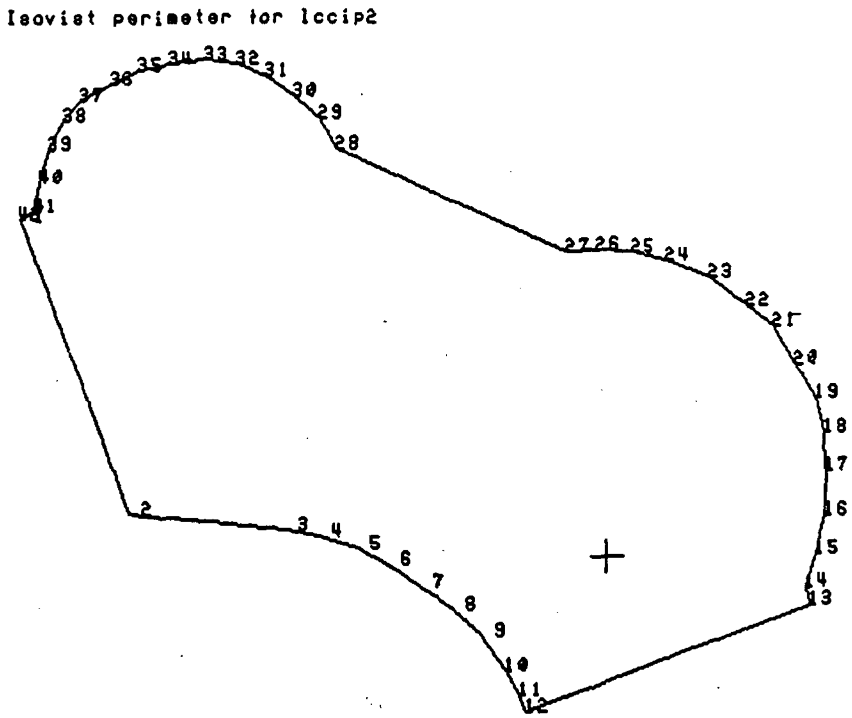


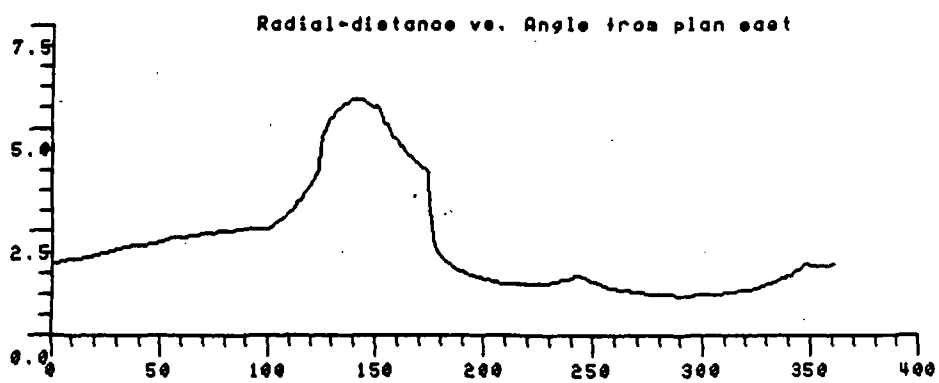


ISOVIST file lccip3	
Isovist Area (A) =	20.789
Total Perimeter (T) =	18.999
Occlusive perimeter(Q)=	1.499
Visible Perimeter (P) =	17.500
R-min =	0.985
R-max =	5.800
R-mean =	2.211
Variance (M2) =	1.736
Skewness (M3) =	3.602

Un-rotated position.	
Variability (lamda) =	0.937
Compactness (C) =	17.364
Circularity (N) =	1.382
Q/P =	0.086
Q/T =	0.079
M2/A =	0.083
M3/A =	0.173

Figure 40



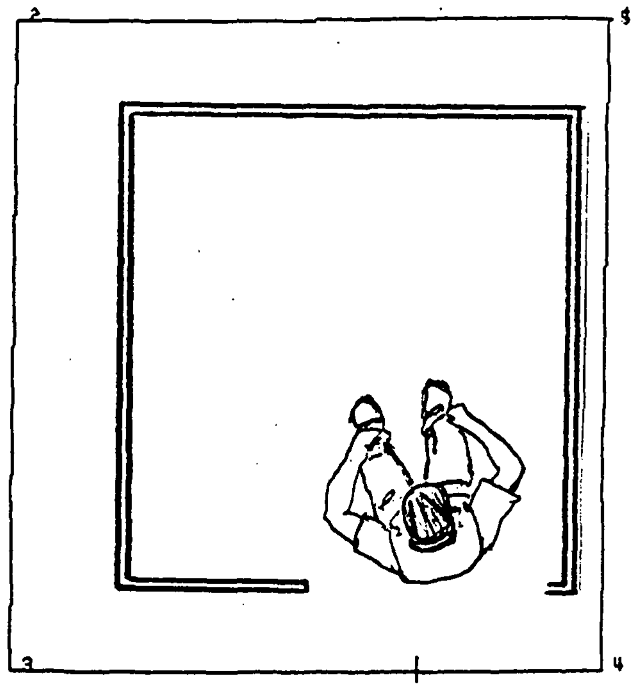


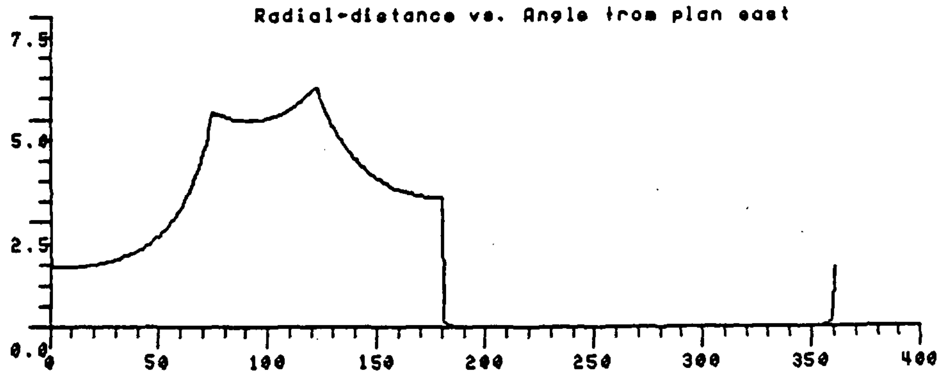
ISOVIST file lccip2	
Isovist Area (A) =	20.751
Total Perimeter (T) =	18.943
Occlusive perimeter(Q) =	1.882
Visible Perimeter (P) =	17.060
R-min =	0.955
R-max =	5.727
R-mean =	2.199
Standard Deviation =	1.328
Variance (M2) =	1.764
Skewness (M3) =	3.233

Un-rotated position.	
Variability (lamda) =	0.849
Compactness (C) =	17.292
Circularity (N) =	1.376
Q/P =	0.110
Q/T =	0.099
M2/A =	0.085
M3/A =	0.158

Figure 41

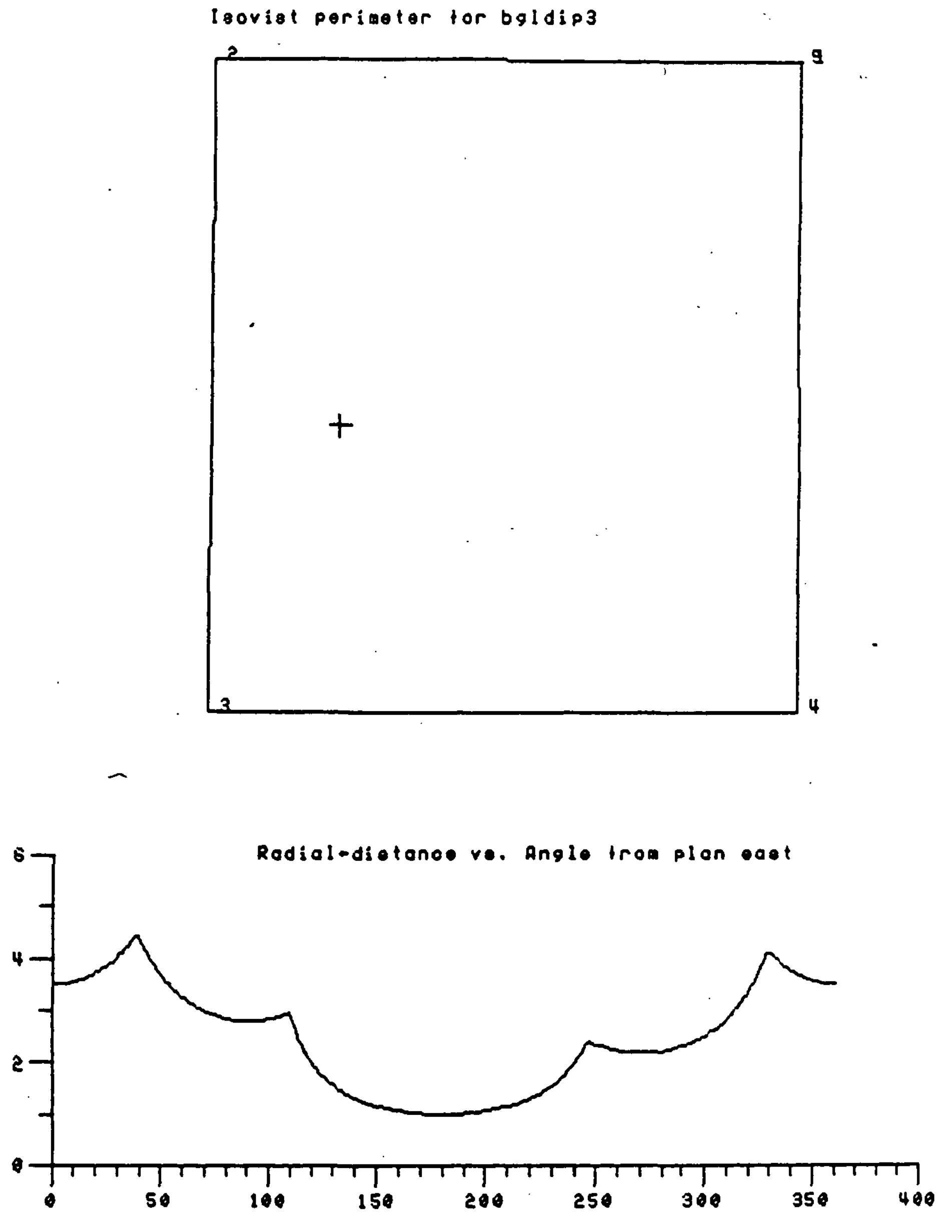
Isovist perimeter for bgldipl





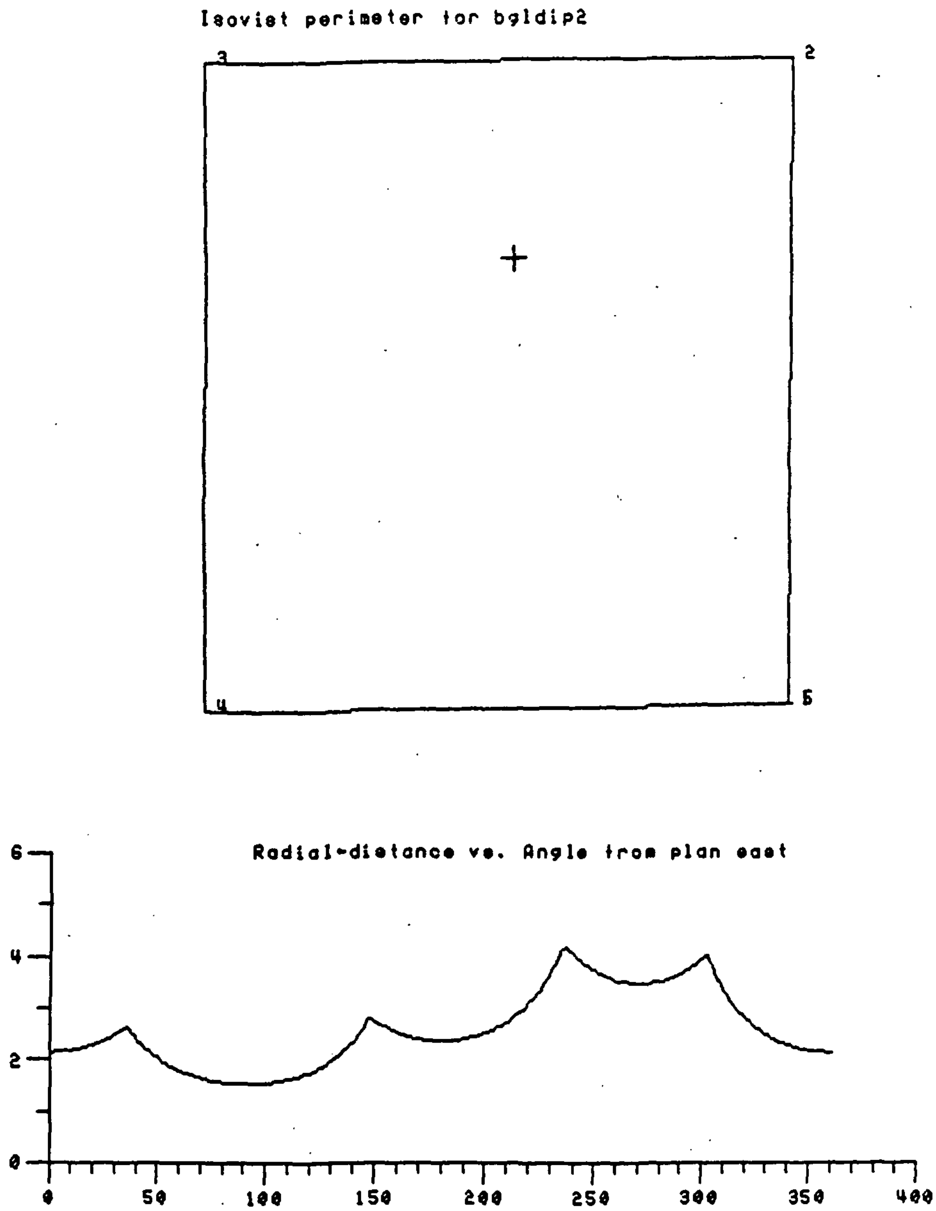
ISOVIST file bgldipl		Un-rotated position.	
Isovist Area (A) =	22.270	Variability (lamda) =	0.930
Total Perimeter (T) =	18.929	Compactness (C) =	16.089
Occlusive perimeter(Q)=	0.000	Circularity (N) =	1.280
Visible Perimeter (P) =	18.929	Q/P =	0.000
R-min =	0.003	Q/T =	0.000
R-max =	5.775	M2/A =	0.181
R-mean =	1.753	M3/A =	0.230
Standard Deviation =	2.006		
Variance (M2) =	4.025		
Skewness (M3) =	5.116		

Figure 42



ISOVIST file bgldip3		Un-rotated position.	
Isovist Area (A) =	22.315	Variability (lamda) =	1.076
Total Perimeter (T) =	18.960	Compactness (C) =	16.110
Occlusive perimeter(Q)=	0.000	Circularity (N) =	1.282
Visible Perimeter (P) =	18.960	Q/P =	0.000
R-min =	0.992	Q/T =	0.000
R-max =	4.429	M2/A =	0.047
R-mean =	2.482	M3/A =	0.001
Standard Deviation =	1.021		
Variance (M2) =	1.043		
Skewness (M3) =	0.012		

Figure 43



ISOVIST file bgldip2

Isovist Area (A) =	22.604
Total Perimeter (T) =	19.040
Occlusive perimeter(Q)=	0.000
Visible Perimeter (P) =	19.040
R-min =	1.525
R-max =	4.197
R-mean =	2.575
Standard Deviation =	0.731
Variance (M2) =	0.535
Skewness (M3) =	0.175

Un-rotated position.

Variability (lamda) =	0.938
Compactness (C) =	16.039
Circularity (N) =	1.276
Q/P =	0.000
Q/T =	0.000
M2/A =	0.024
M3/A =	0.008

Figure 44

predict that the Sky1p compartment should have been regarded as most spacious, on the basis of its greater isovist area and variance. Sky2p and Sky3p are much closer in size. But if variance and elongation are as important as the literature suggests, and if low lambda improves spaciousness, then Sky3p should have been judged slightly more spacious than Sky2p.

Unfortunately, we could find no reference to differences in judged spaciousness in the published Skylab literature. Perhaps this question was never asked(?). As a relatively quick test of the validity of isovist theory for crew compartments, it deserves to be answered now. We encourage our readers to help in this regard.

Concluding Discussion of Isovist Theory and Spaciousness

Our simulations have shown that isovist theory is sensitive enough to capture differences in visible space within small crew compartments. Although isovist theory is a relatively recent development, its predictions also seem to reaffirm the results of earlier published studies on spaciousness and perceived volume. Whether those investigators knew it or not, they were manipulating isovist characteristics as independent variables, and their results are in accord with those of the one published paper (Benedikt and Burnham 1985) that explicitly used isovist measures.

The available evidence indicates that enclosed volumes may be made to appear more spacious if they are not compact (i.e., have higher values on isovist compactness and circularity measures), allow longer axial views (i.e., have higher variance), and have more visible space (i.e., have greater isovist area) from comparable vantage points. We can also define another isovist measure of visual complexity that deals with sequential dependency in the isovist array (lambda). This measure seems not to have been investigated in studies of perceived volume, but it is useful in two ways.

First, in terms of a full (360^0) isovist, low levels of lambda may indicate a less chaotic-appearing room boundary which we would expect to be associated with higher judged spaciousness. For example, Samuelson and Lindauer (1976) found that a neat room, with everything organized, was judged as larger and emptier than a messy room of equal size and furnishings. This seems to confirm the interior designer's heuristic of increased spaciousness accruing from "the eye's ability to move easily over a room." Second, if we consider only a partial isovist, such as a view along an enclosing edge or surface, we find that lambda is higher for views along a curved edge/surface receding from the observer than for a lineal one. However, Della Valle et al. (1956) found that, with two-dimensional figures (seen in plain view), if an edge is broken or curved there is a greater overestimate in line length when compared to a straight line. This might indicate that <u>higher</u> lambda values in receding edges should be desirable so that when one looked along a curving bulkhead within an enclosure, spaciousness would be heightened.

We believe it is dangerous to generalize from paper and pencil studies of figures to prediction about perceived qualities of enclosing volumes. Simulation research needs to be done to determine if changes in the angularity or curvature of bulkheads can be used to enhance spaciousness.

Isovist theory, however, provides the necessary tool for investigating such manipulations. Table I summarizes isovist characteristics for various cabin proposals and room shapes, ordered by increasing elongation.

Insert Table 1

AFFECTIVE CONNOTATIONS

When one views or lives in an enclosed space, different emotions--or affective connotations--may be induced in the user. Since architects are very concerned with affective qualities of spaces, there has been a substantial history of investigation in this area.

Unfortunately, most all of these studies did not manipulate volume or geometry of rooms independently from a myriad of other design characteristics. There have also been serious problems with the prime methodology--the use of bipolar semantic differential scales (see Danford, Starr & Willems 1979, for a discussion of these problems).

In spite of the valid criticisms, the idea that spaces carry affective connotations seems well established. For example, Kuller (1974) reports that factor analytic studies of 66 adjective responses to slides of apartments could be analyzed in terms of a smaller number of "affective" factors. The first, and most important, was security; the second, social status; the third, physical arrangement, and the fourth, individuality. So spaces carry meanings for people beyond their purely physical measures.

TABLE 1

ISOVISTS FROM ENTRY POSITIONS

Crew Quarters

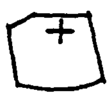
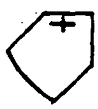
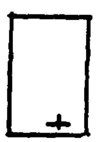
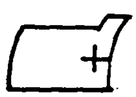
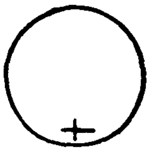
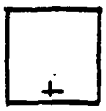
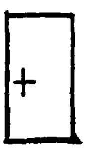
	C / N	M_2	M_2/A	Lamda	Area
	15.15/1.21	1.58	0.17	0.97	9.55
	15.30/1.22	1.85	0.19	0.90	9.84
	16.09/1.28	4.03	0.18	0.93	22.27
	16.34/1.30	1.73	0.18	0.93	9.90
	16.46/1.31	2.15	0.19	0.87	11.43
	17.75/1.41	3.01	0.16	1.31	18.48
	19.11/1.52	2.50	0.20	0.97	12.61

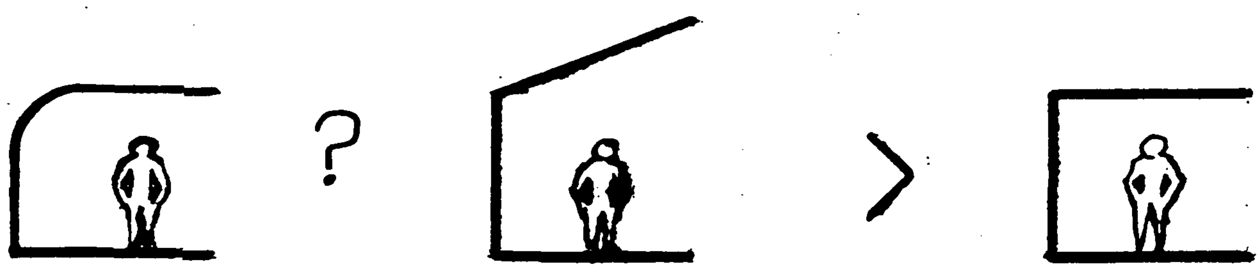
TABLE 1 (continued)

Shapes (Area Held Constant)

	C / N	M_2	M_2/A	Lamda	Area
	12.59/1.00	2.46	0.16	1.23	15.01
	15.48/1.23	2.30	0.15	0.93	14.97
	16.00/1.27	2.17	0.14	0.95	15.05
	16.32/1.30	2.34	0.16	0.93	15.09
	17.07/1.36	2.00	0.13	0.89	15.00
	17.07/1.36	2.47	0.17	1.01	15.00

What kind of affective connotations would we like the interior of a space station to have and what evidence exists regarding the impression given by certain kinds of enclosing shapes?

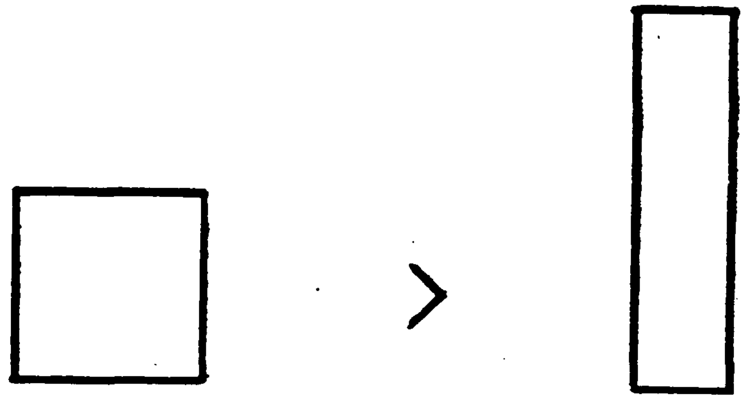
In one of the earliest relevant studies, Wools and Canter (1970) found that a sloped ceiling in a drawn room made that room appear much more friendly than if it had a flat ceiling, although this was not as important as seating arrangement.



Garling (1972) studied aesthetic preferences using color photographs and detailed and nondetailed drawings of streets in a small town. He found that high values of "pleasantness" could be accounted for by three factors. The first factor he called variation, which referred to variation in shapes, sizes, and colors, and richness of detail. The second factor was shadiness and had to do with variegated light quality in the scene. The third factor was openness and dealt with size and lightness of spaces. Whereas more variation and shadiness resulted in greater pleasantness, subjects were divided on their opinions about openness.

A more thorough study of the influence of spatial configurations on affective responses has been recently completed by Nasar (1981). He had 120 respondents sort 1/12-scale room models in terms of felt security, pleasantness and interest. He found that models with average-height ceilings were felt to be more secure than those with tall ceilings; that square models were judged more pleasant than rectangular ones; and that wide spaces were judged more secure, pleasant and interesting than narrow ones. His definition of wide and narrow was not made in terms of aspect ratio of the rooms, but in terms of absolute width. His narrow models were all 12.7 cm in breadth by either 25.4-cm or 50.8-cm. long. His wide model was 25.4 cm by 50.8 cm.

Much of Nasar's (1981) results can be interpreted as a favorable response to spaciousness, since larger area models were more favorably rated, and the most favorable of all were those with the lowest height/depth ratio. This latter measure has been shown (Hayward and Franklin 1974) to strongly influence perceived enclosure. But even if Nasar's data are regrouped so that volume is controlled, it appears that square rooms, with or without tall ceilings, are judged more favorably in terms of security, pleasantness and interest than are rooms of aspect ratio 4:1.



Taken together, the results of these different studies suggest that changes in the isovist characteristics of interiors are likely to influence more than perceived spaciousness, and that some manipulations may produce undesirable affective responses as a side effect.

Sloping ceilings would seem to be positive for both spaciousness and the connotation of friendliness, since they produce an increase in the isovist variance. (We wonder if a bulkhead that <u>curves</u> into a ceiling would show a response similar to thalopedgivenceilings.Together with Garling's (1972) study, it seems clear that a high isovist variance is desirable for an interior volume.

But Nasar's results imply a preference for square, compact spaces over rectangular ones, and this is contrary to the desired effect that elongation and rectangularity have on perceived spaciousness. However, in his study, this only became apparent when he contrasted square spaces with those of 4:1 aspect ratio, which is a much higher aspect ratio than that which previously enhanced perceived volume. Given the results of the other investigators cited here, it seems reasonable to say that spaces with aspect ratios of 2:1 to 2.5:1 could be utilized to enhance spaciousness without undesirable affective connotations. Again, clearer evidence awaits simulation tests that assess both spaciousness and affective response concurrently.

Another recent study by Kaye and Murray (1982) demonstrated the interaction that furniture density has with perceived room size. In their factor analytic study of colored room drawings, they found that additional furniture in a pictured room made the room appear more "cluttered" and "accidental" as well as less spacious. (This reaffirms the finding of Samuelson and Lindauer 1976.)

There appears to be a good lesson here for the design of tight spaces. Not only the shape of the room, but also the way furnishings are placed within it, will affect perceived spaciousness. The impression given by a small volume requires that geometry and furnishings work together to create a well-integrated space. From a human factors perspective, the visual satisfaction with a crew compartment, in terms of spaciousness and other affective connotations, will depend on how well requisite features such as a sleep restraint, storage and work/communication center all fit within the envelope.

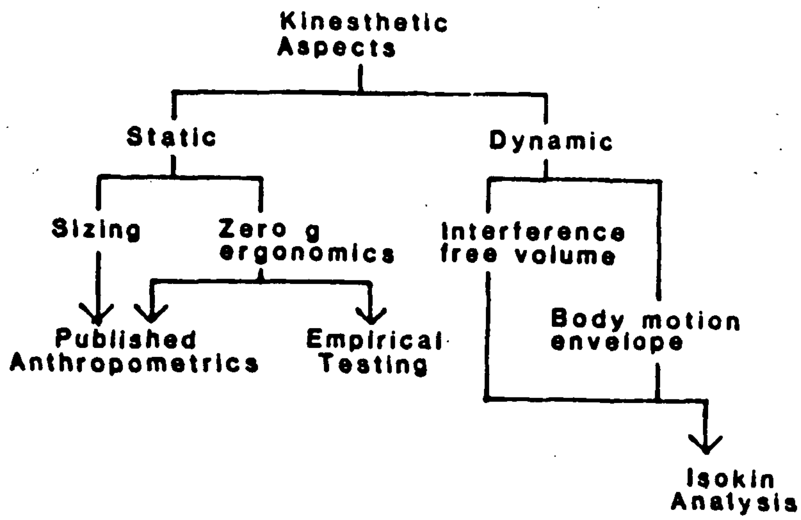
Concluding Comments on Visual Aspects

This section has reviewed the visual aspects of spatial habitability and proposed an analytic model in the form of isovist theory as a design tool.

Extant literature confirms that small spaces may be made to appear more spacious by manipulation of their geometry, the addition of views out of the space, and careful integration of their furnishings. Isovist theory provides a direct means of measuring the visual qualities associated with spaciousness and other affective connotations of an enclosure. It is also congruent with the tenets of ecological optics while being applicable to any size or configuration of interior space.

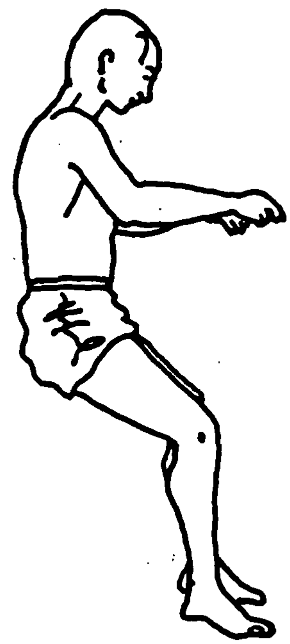
Substantive results of earlier studies, though incomplete, are remarkably convergent in their implications for expanding perceived volume as well as for enhancing the affective components of settings. Many of those investigators' manipulations of spatial variables are interpretable within isovist theory, which would allow future simulation studies to build on these results in order to assess a wide range of interior spatial qualities. The visual aspects of human spatial habitability become operational and measurable within the model presented here, and are readily amenable to rigorous empirical testing.

KINESTHETIC ASPECTS



The kinesthetic aspects of human spatial habitability are concerned with the ways that people fit in and move through interior spaces. Our structural tree divides these aspects into static and dynamic conditions, respectively.

Static conditions involve accommodating the size of crew members as well as their postures. Earlier missions have provided a wealth of data regarding the significant changes in body measurements and postures that are seen as adaptations to a microgravity environment. (See the Skylab Experience Bulletins for a more complete discussion of these effects.) Generally, there are increases in torso girth as body fluids shift headward, and concomitant decreases in leg girth. Also, a person's extended height increases as spinal loads diminish under micro g. Posturally, the resting position becomes more quadrupedal, with arms and legs raised and bent forward while the head and neck bend downward.



As the Skylab missions demonstrated, these bodily changes have significant implications for the design of equipment, furnishings and interior space (Pogue 1985; Cooper1976; Compton and Benson 1983). Astronauts often had to tense their stomach muscles uncomfortably to remain "seated" at a console and could not use leg/thigh restraints in their proposed manner.

Clearly, the ergonomics of zero-g conditions are different from terrestrial environments. While acknowledging the importance of these anthropometric transformations, this study will not attempt to address such static qualities of kinesthetic spatial habitability, as they are well-presented elsewhere (Griffin 1978).

C-2

Dynamic aspects of the human form produce equal, but as yet unaddressed (Church et al. 1976), concerns for habitability. Tight spaces require adaptations in human motion patterns to keep the body motion envelope (bme) as small as possible. Contrast, for a moment, the act of getting dressed in one's bedroom or in a one-person mountain tent. In the latter, feet are kept close together, bending angles are reduced, and a shirt is most likely donned one arm at a time.

In a confined space, movement patterns that typify any number of daily activities must often be contracted and reduced in variability so as to fit within the available volume. One can study these dynamic phenomena in two ways--by looking at either the interference-free volume or the body motion envelope.

Interference-free volume measures the unobstructed physical space available for a particular action. The body motion envelope is an integration, over time, of the actual amount and shape of space swept out by an activity.

Both of these considerations were examined by Church et al. (1976) in their determination of space requirements for the STS bunks and hygiene station. The bunk space was specifically sized to allow a 95th-centile male to turn over or to raise the knee to a vertical position while lying prone.

Sometimes very small amounts of additional space can make considerable differences in human comfort, if the space is where it is needed.

Sanders (1980), for example, investigated the dimensions of sleeping cabs in cross-country trucks. He found that the berth dimensions needed to be increased by only 0.2 m in width in order to comfortably accommodate the desired, slightly curled, sleep posture. Although cabs were anthropometrically sufficient for straight prone sleeping, they could be significantly improved by a minor increase that allowed a larger variety in body positions.

Succinctly, the lesson here seems to be straightforward: dimensional increases do not enhance habitability unless they occur where needed; because in essence, it is not how large you make a space, it is how you make it large.

From this perspective, then, arguments over how much volume is sufficient for habitation are likely to be inconclusive as long as there is no general analytical procedure for determining where and how an enclosure induces constraints or requires adaptations on human movement. We could find no extant technique suitable for this purpose; however, it was possible to combine some features of the isovist model with physical space-modelling techniques to utilize both requisite free volume and body motion concepts. We have called this ISOKIN ANALYSIS.

<u>Isokin Analysis</u>

Figures 45 and 46 illustrate the essential idea of ISOKIN analysis, where the ISOKIN is defined as that space available for a given set of movements from a given point.

Insert Figures 45 and 46

In ISOKIN analysis, the outer contour of figures 45 and 46 represent the actual physical enclosure of space, not the visible space defined by isovist analysis. Two-dimensional illustrations of these spaces represent a section taken through the space and enclosures parallel to the x-y plane. The inner contour is a similar section of a body motion envelope (bme) taken parallel to the x-y plane. The diagram illustrates how the body-centered coordinate system (x', y',z') may be referenced to the fixed x, y, z system attached to the enclosure. Vectors R_1, R_2, and R_3 comprise both the scalar length and angular information necessary to uniquely locate the x', y', z' axis (i.e., body). Body orientation is defined within the enclosure by comparing relative orientation of x, y, z and x', y', z' axes.

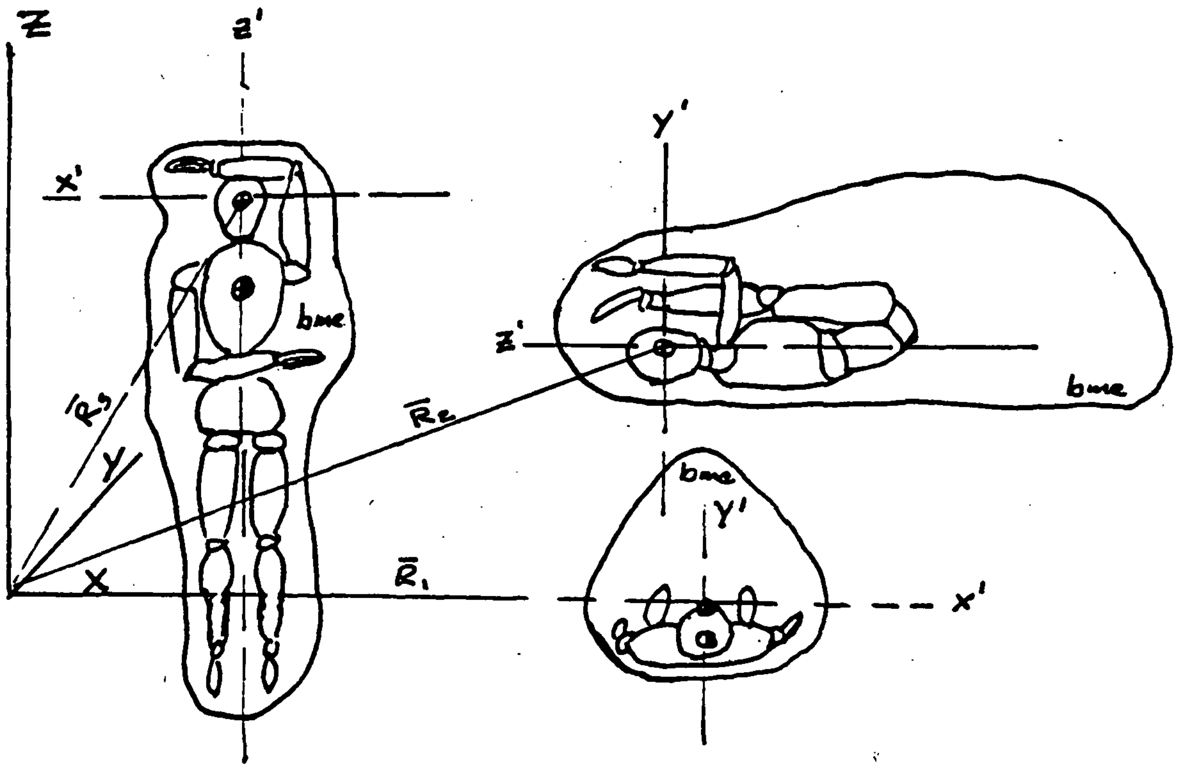
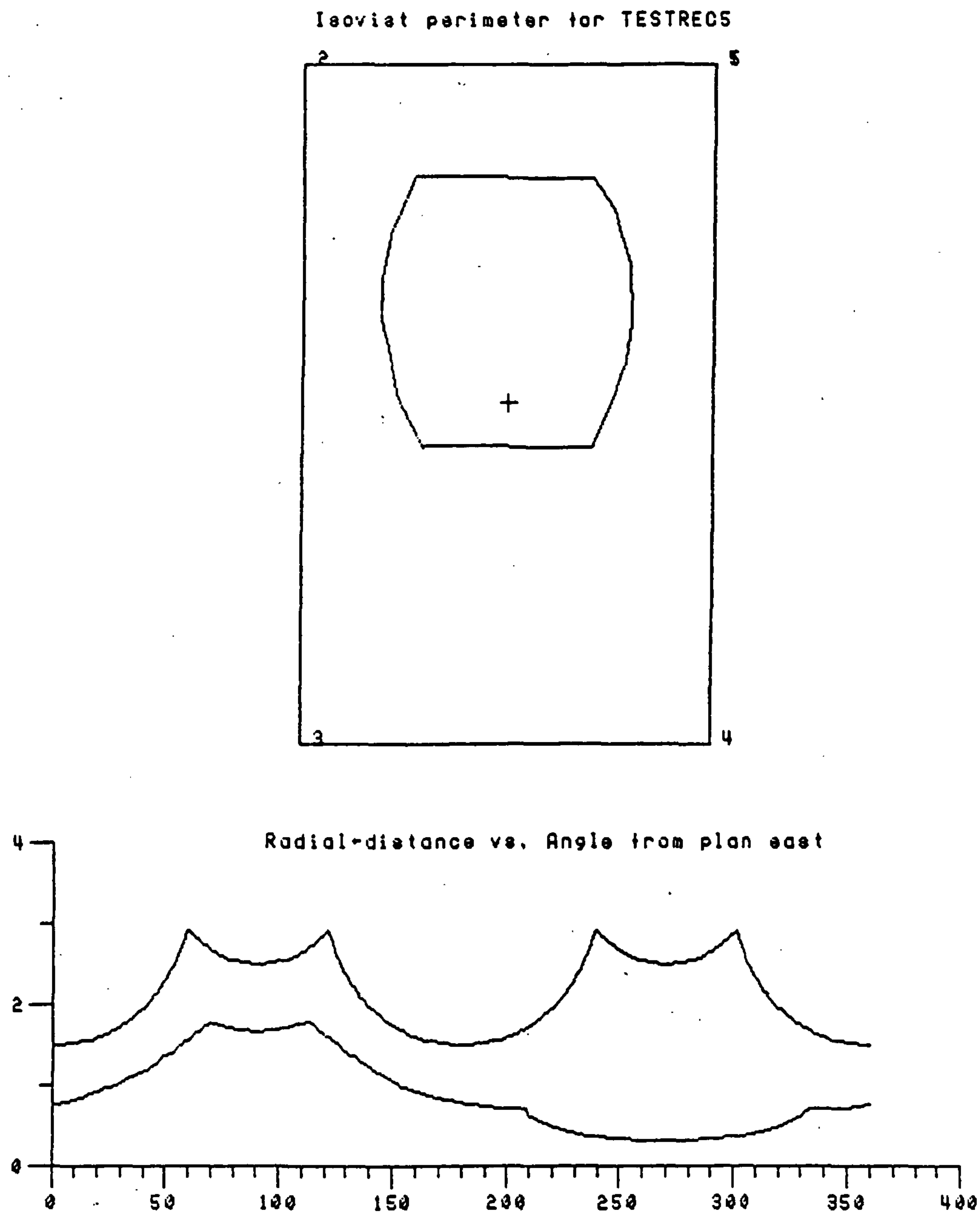


Figure 45 represents a maximal section through the resting 0-g posture bme of a 5th-centile female in a cylindrical enclosure. Figure 46 places this



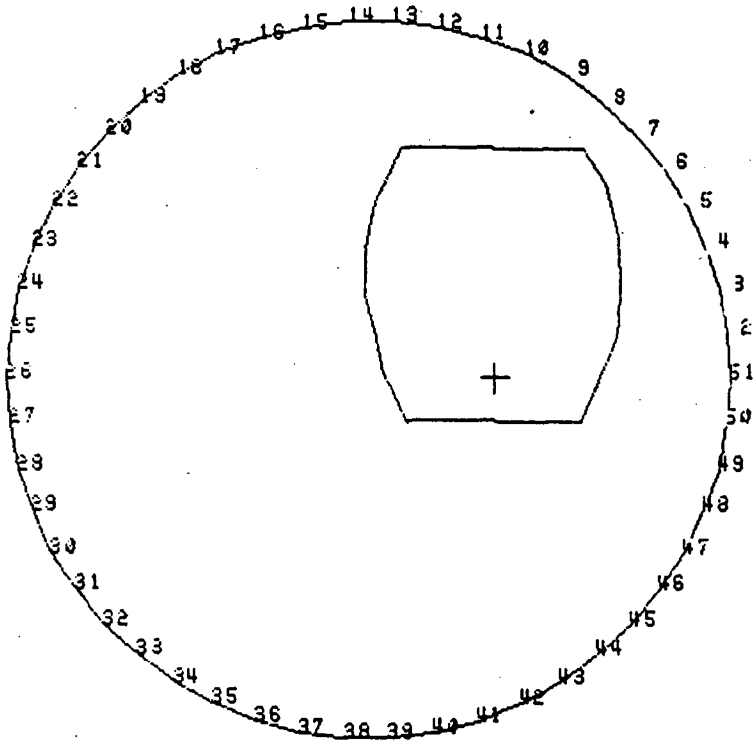
ISOVIST file TESTREC5
BME file NBPS

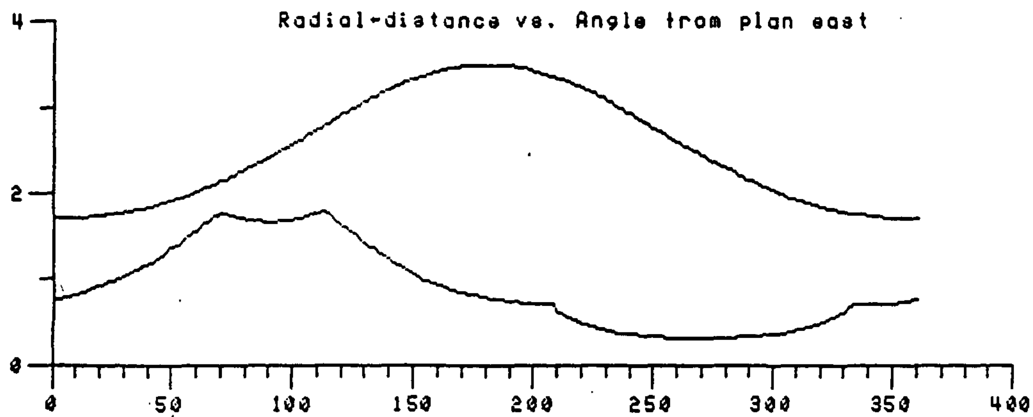
Un-rotated position.

Isovist Area (A) =	15.000	Variability (lamda) =	1.143
Total Perimeter (T) =	16.000	Compactness (C) =	17.067
Occlusive perimeter(Q)=	0.000	Circularity (N) =	1.353
Visible Perimeter (P) =	16.000	Q/P =	0.000
R-min =	1.500	Q/T =	0.000
R-max =	2.912	M2/A =	0.016
R-mean =	2.131	M3/A =	0.000
Standard Deviation =	0.482	Isovist form-factor =	1.333
Variance (M2) =	0.233	BME form-factor =	1.050
Skewness (M3) =	0.002	Gross Free Area (GFA) =	0.782

Figure 45

Isovist perimeter for CIRCR95





ISOVIST file CIRCR95
BME file NBP5

Un-rotated position.

Isovist Area (A) =	21.178	Variability (lamda) =	1.090
Total Perimeter (T) =	16.325	Compactness (C) =	12.584
Occlusive perimeter(Q)=	0.000	Circularity (N) =	1.001
Visible Perimeter (P) =	16.325	Q/P =	0.000
R-min =	1.697	Q/T =	0.000
R-max =	3.500	M2/A =	0.019
R-mean =	2.517	M3/A =	0.002
Standard Deviation =	0.638	Isovist form-factor =	1.001
Variance (M2) =	0.408	BME form-factor =	1.050
Skewness (M3) =	0.050	Gross Free Area (GFA) =	0.846

Figure 46

section in a rectangular surround. The lower graph on the accompanying twin plot is for the bme, the upper for the enclosure. (Volume may be converted from surface areas by multiplying by the average assumed height of 7 feet.)

As with isovists, it is first necessary to define some new measures in order to fully utilize ISOKIN analysis.

DEFINITIONS:

ACTIVITY: A logically or habitually related sequence of body motions

BODY MOTION ENVELOPE (BME): A conceptual surface which just encloses the extreme body motion of an activity

GROSS FREE AREA AND GROSS FREE VOLUME: The area or volume defined by the enclosing surface minus the area or volume of the bme. (Equipment or furnishings are not included in our test contours, but should be included in practical applications.)

GROSS FREE AREA (VOLUME) RATIO: The ratio of gross free area (volume) to the total area (volume) of the enclosure

INTERFERENCE-FREE VOLUME: The useable volume within an enclosure for a specific bme. This volume will usually be less than the gross free volume, because it is affected by projections or acute angles in the enclosure that constrain placement of a bme. Interference-free volume is determined piecemeal by moving sections of a bme around in an enclosure until a part of the bme contour touches an edge or limiting projection. This envelope of unrestricted movement (corresponding to planar translations and rotations of a "rigid" bme section) is the interference-free area. When added up for different bme sections, and adjustments made for whole body restrictions, it becomes the interference-free volume. A familiar example of a design's effect on interference-free volume occurs with the length of the arms on a standard desk chair. As the sitter brings the chair closer to the edge of the desk in order to write on the desktop, the projecting arms of the chair are the first elements to strike the desk edge, impinging further movement. The sitter is subsequently forced to lean forward, which does not allow the seat-back cushion to support his/her lumbar area. Modern ergonomic desk chairs have "recessed" arms that permit closer chair placement and the needed back support. In this example, the interference-free volume in the chair movement envelope is substantially and selectively increased by a relatively small design change.

ADAPTATION INDEX (AI): Percent of BME Area outside enclosure,
$AI = A_{bme}$ outside/A_{bme} total x 100

KINESTHETIC EFFICIENCY (KE): The definition of Gross Free Area/Volume (GFA) and Interference-free Area/Volume (IFA) allow specification of Kinesthetic Efficiency (KE) as a measure of spatial economy. KE is the percentage of space utilizable by a bme compared with the space provided by the enclosure.

$KE = (IFA/GFA) \times 100$

The computation is identical for volume measures.

THE FORM FACTOR: A ratio which compares the longest dimension between two points within a bme or enclosure to the diameter of a circle having the equivalent area as the bme or enclosure (Bunge 1962: Haggett and Chorley 1969).

$FF = L/d$

Form Factors greater than 1.00 show increasing elongation of a bme or enclosure.

CONFORMITY INDEX: A measure which compares the form factors of bme and Enclosure by taking their difference

$CI = FF(enc) - FF(bme)$

The Conformity Index is considered to be more efficient as it is closer to zero, for this indicates a shape of space similar to the shape of the bme it encloses. But Conformity Index will not indicate free volume.

RADIAL INTERFERENCE MARGIN (RIM): A measure of the accommodation of a space to the preferred location of an activity. It is defined as the radial separation (+) or overlap (-) of a preferentially located bme within the enclosure when the maximum radial of the bme (R_{max}) is aligned with the minimum radial of the enclosure.

$RIM = R_{min}(encl) - R_{max}(bme)$

PERCENTAGE OF RADIAL INTERFERENCE (PRI)/ ACCOMMODATION: The ratio of the RIM over the R_{max} (bme) times 100. When it is negative, it is the highest percent of R_{max} (bme) undergoing interference. When it is positive, it is the percent of the R_{max} bme that is "overaccommodated" in the space.

TOTAL ANGULAR INTERFERENCE (TAI): The total number of degrees through which contact is observed between a rotating preferentially located bme and an enclosure.

QUALITY OF INTERFERENCE Is an indicator of the severity of any contact between bme and enclosure. The QOI for one contact point

(QOI): may be approximated by calculating the angle between the enclosure surface (or surface tangent) and the bme surface tangent at the contact point. Smaller average contact angles indicate less severe contacts as long as velocity vectors parallel to the bme envelope are assumed.

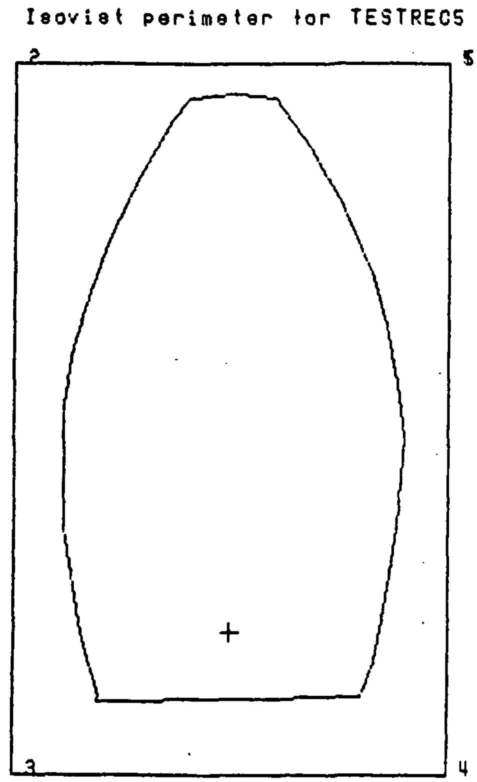
The interpretation of RIM, PRI, and TAI measures first requires specification of how desirable it is to allow rotation of a located bme within an enclosure. Figure 47 shows these measures for a 95th-centile male in a forward bend or leg elevation (shoe tying) bme within a rectangular enclosure. Notice that translation of the (lower) bme curve along the x-axis corresponds to a rotation of the bme in the space.

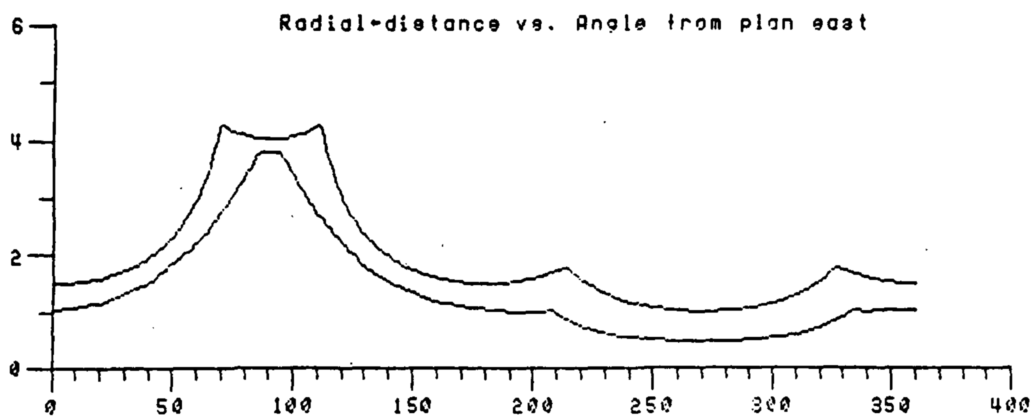
Insert Figure 47

The above definitions of measures and criteria for whole bmes within enclosures correspond to some underlying hypotheses about kinesthetic spatial habitability:

A. A space is more habitable if it allows an activity or set of activities to be performed in alternative positions within the space (placement of bmes).

B. A space is more habitable if it allows an activity or set of activities to be performed in more than one specific way (variability of bme).





ISOVIST file TESTRECS
BME file BENDS5

Un-rotated position.

Isovist Area (A) =	15.000	Variability (lamda) =	0.922
Total Perimeter (T) =	16.000	Compactness (C) =	17.057
Occlusive perimeter(Q)=	0.000	Circularity (N) =	1.358
Visible Perimeter (P) =	16.000	Q/P =	0.000
R-min =	1.000	Q/T =	0.000
R-max =	4.257	M2/A =	0.062
R-mean =	1.961	M3/A =	0.079
Standard Deviation =	0.964	Isovist form-factor =	1.218
Variance (M2) =	0.929	BME form-factor =	1.317
Skewness (M3) =	1.190	Gross Free Area (GFA) =	0.455

Figure 47

C. A space is more habitable if it is as accommodating to the largest person's bme as it is to the smallest person's (same) bme (sizing of a bme).

As an explanatory demonstration of ISOKIN analysis, figures 47 and 48 show two bme profiles for 95th-centile males inserted in different sections of 150 ft^3 spaces. The "bend" bme represents a shoe-tying motion.

Insert Figure 48

Note that for the "bends" in Figures 47 and 48, the Conformity Index in the rectangular space is better, but the cylindrical space has greater interference-free area, and thus, kinesthetic efficiency. The bme is very elongated and directional when compared to a circular surround, which interferes with the bme slightly more in terms of radial and angular variation. But for these size spaces, there are far more accommodating positions for the bme in the circular space than in the rectangular one.

In Figures 49 and 50, the bend bme is replaced by a "reach" for the same size male. The "reach" bme represents a standing reach and full horizontal arm swing to the sides. The Conformity Index here again favors the rectangular space which better matches the elongation of the bme. Also, there is less overlap with the rectangular enclosure, meaning that less adaptation of the bme would be needed in the rectangular space.

Insert Figures 49 and 50

When rotations of the bme are taken into account, however, the circular surround shows a distinct advantage in the percentage of radial

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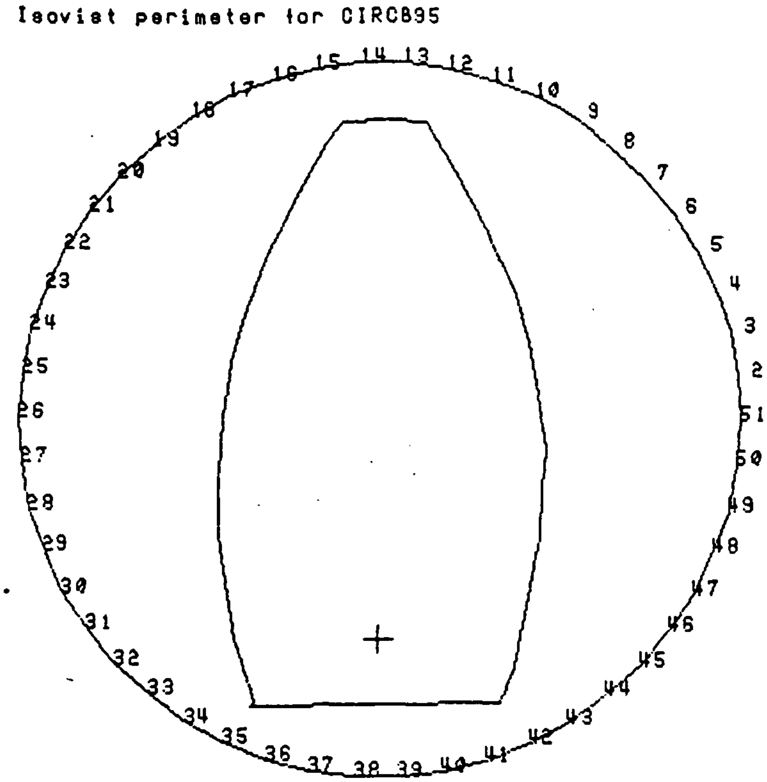

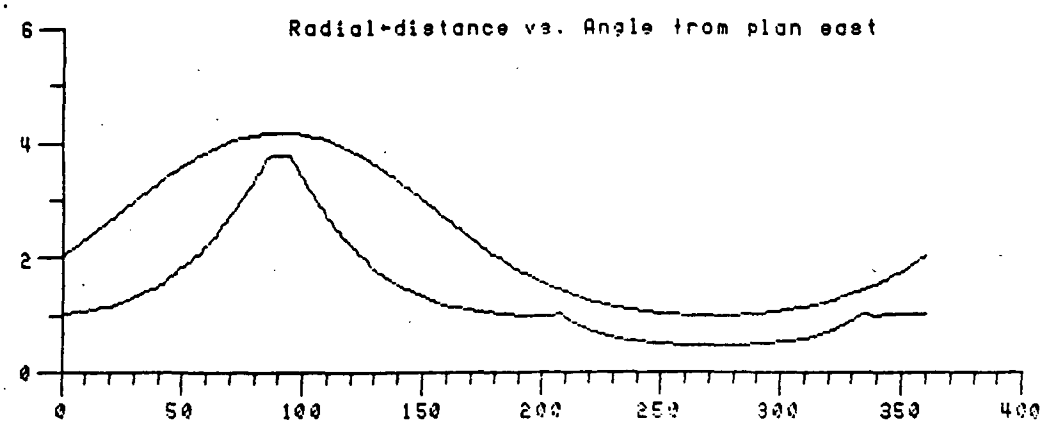

ISOVIST file CIRCB95
BME file BEND95

Un-rotated position.

Isovist Area (A) =	21.178	Variability (lamda) =	0.331
Total Perimeter (T) =	16.325	Compactness (C) =	12.594
Occlusive perimeter(Q) =	0.000	Circularity (N) =	1.001
Visible Perimeter (P) =	16.325	Q/P =	0.000
R-min =	0.390	Q/T =	0.000
R-max =	4.193	M2/A =	0.062
R-mean =	2.328	M3/A =	0.025
Standard Deviation =	1.149	Isovist form-factor =	0.999
Variance (M2) =	1.320	BME form-factor =	1.317
Skewness (M3) =	0.524	Gross Free Area (GFA) =	0.614

Figure 48

Isovist perimeter for RECB95

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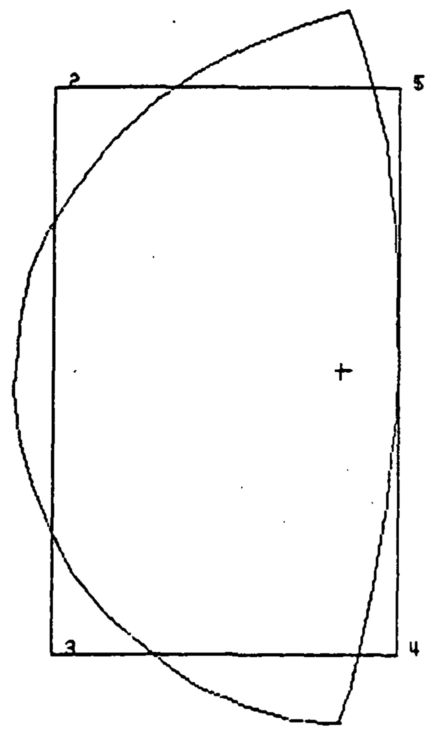
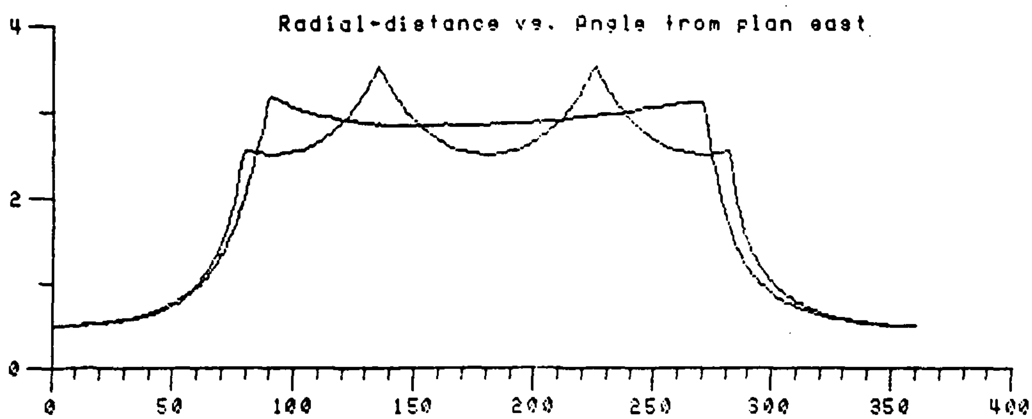


Radial-distance vs. Angle from plan east

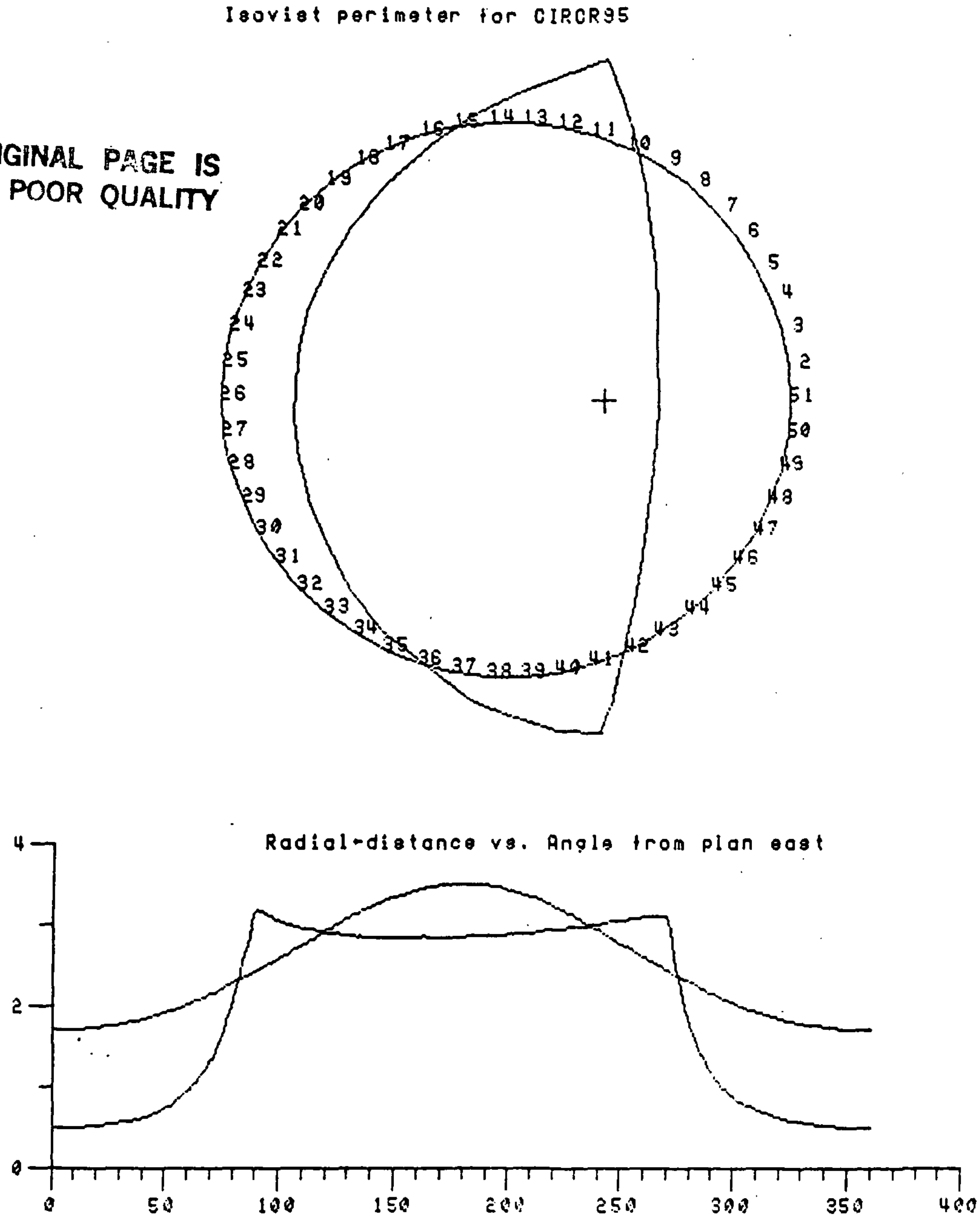


ISOVIST file RECB95
BME file REACH95

Un-rotated position.

Isovist Area (A) =	15.000	Variability (lamda) =	1.120
Total Perimeter (T) =	16.000	Compactness (C) =	17.067
Occlusive perimeter(Q)=	0.000	Circularity (N) =	1.358
Visible Perimeter (P) =	16.000	Q/P =	0.000
R-min =	0.500	Q/T =	0.000
R-max =	3.536	M2/A =	0.070
R-mean =	1.929	M3/A =	-0.020
Standard Deviation =	1.027	Isovist form-factor =	1.166
Variance (M2) =	1.054	BME form-factor =	1.405
Skewness (M3) =	-0.304	Gross Free Area (GFA) =	-0.043

Figure 49



ISOVIST file CIRCR95
BME file REACH95

		Un-rotated position.	
Isovist Area (A) =	21.179	Variability (lamda) =	1.030
Total Perimeter (T) =	16.325	Compactness (C) =	12.534
Occlusive perimeter(Q)=	0.000	Circularity (N) =	1.001
Visible Perimeter (P) =	16.325	Q/P =	0.000
R-min =	1.697	Q/T =	0.000
R-max =	3.500	M2/A =	0.019
R-mean =	2.517	M3/A =	0.002
Standard Deviation =	0.638	Isovist form-factor =	1.001
Variance (M2) =	0.408	BME form-factor =	1.405
Skewness (M3) =	0.050	Gross Free Area (GFA) =	0.261

Figure 50

interference (PRI). (This difference would be lessened somewhat if the bme in the rectangular enclosure were shifted slightly to the left.)

These examples show the advantages and disadvantages of using various spaces to enclose elongated or directional bmes. A compact space will likely require more adaptations in body motion to fit the space, but that adapted action can then take place in a greater number of positions. An elongated space will require less adaptation of the motion, but the action will be constrained to relatively fewer positions in the space.

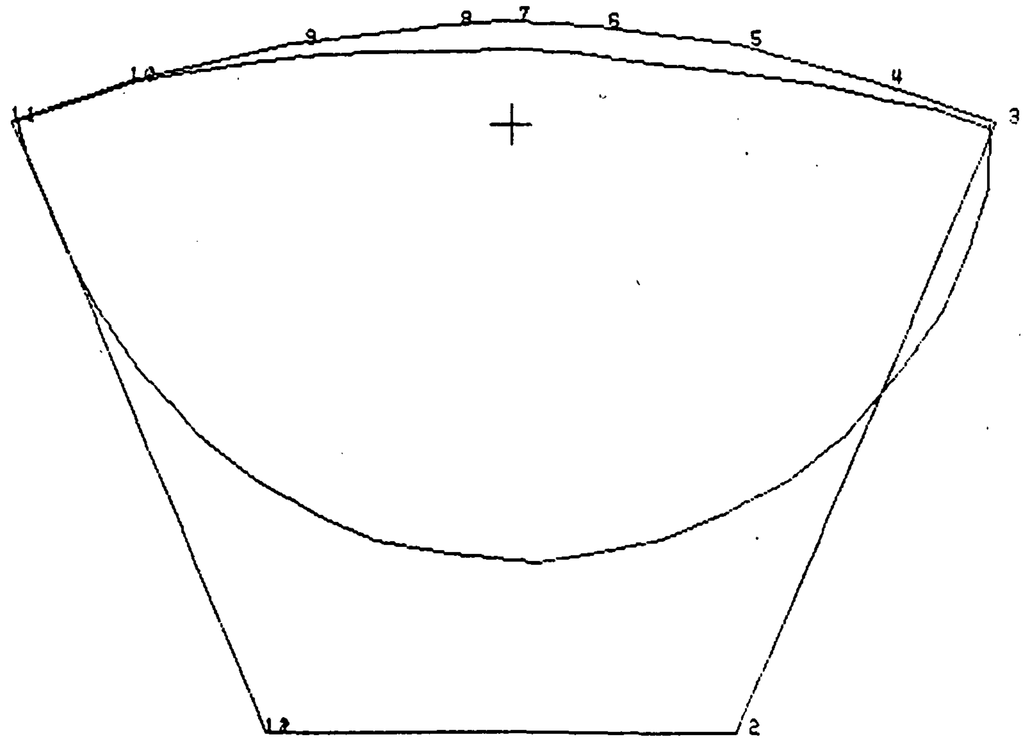
ISOKIN analysis reveals the critical tradeoff demanded in the kinesthetic design of tight spaces. It is a tradeoff of constrained variability. Either an activity will be constrained in the ways it can be performed (adaptation required) or in the positions where it can be performed (no adaptation required).

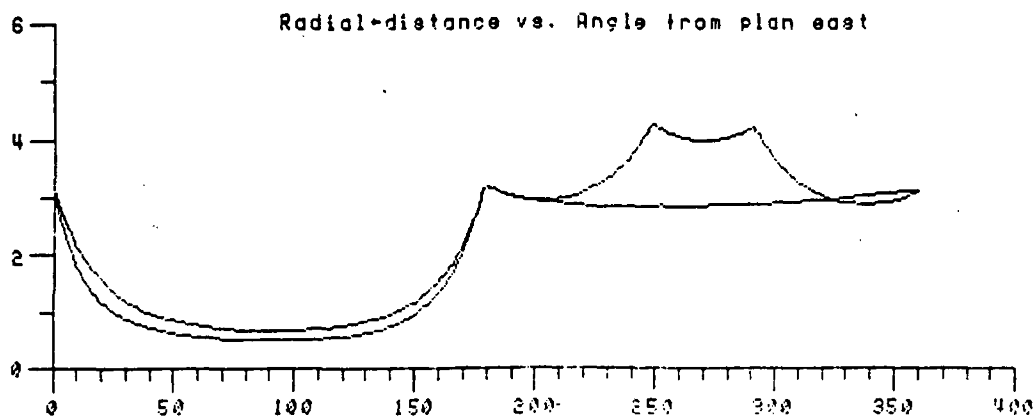
Figures 51 and 52 compare the reach and bend bmes for the same pie-shaped 150-ft^3 space. The pie-shaped space accommodates the bend bme better in its present position and rotated positions (indicated by relative IFA's or KE's and TAI's, respectively) at a cost of greater radial interference (PRI) in most rotated positions.

Insert Figures 51 and 52

Figures 53 through 58 illustrate reach and bend bmes in three different proposed crew-quarter configurations. The ISOKIN analysis of constraints on body motions are both revealing and compelling. Comparison of the ISOKIN

Isovist perimeter for PIER95





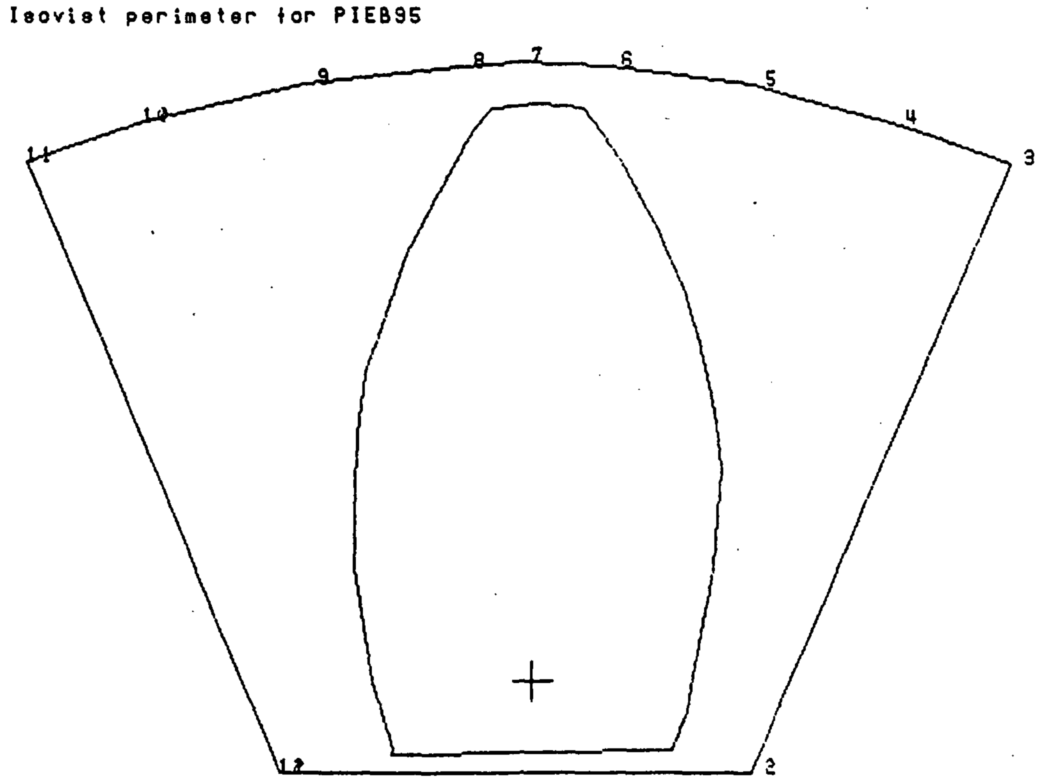
ISOVIST file PIER95
BME file HOREACH95

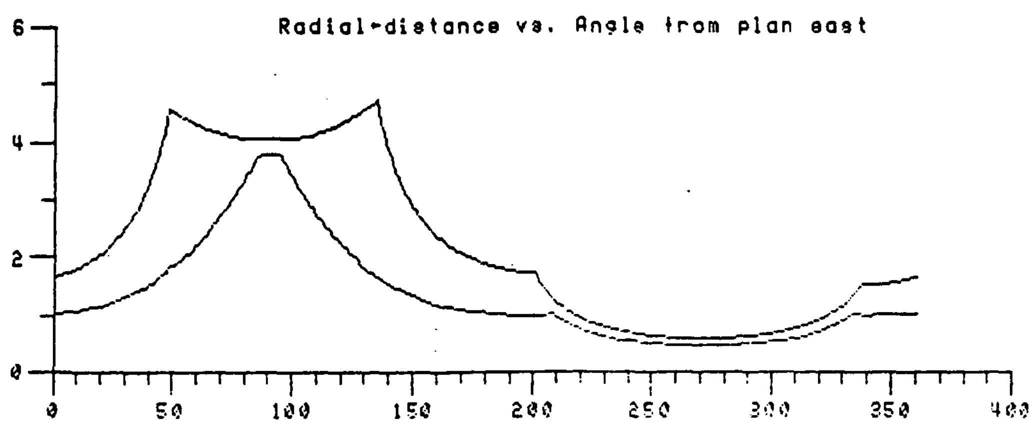
Un-rotated position.

Isovist Area (A) =	21.420
Total Perimeter (T) =	18.201
Occlusive perimeter(Q)=	0.000
Visible Perimeter (P) =	18.201
R-min =	0.577
R-max =	4.252
R-mean =	2.296
Standard Deviation =	1.244
Variance (M2) =	1.547
Skewness (M3) =	-0.088

Variability (lamda) =	0.957
Compactness (C) =	15.465
Circularity (N) =	1.221
Q/P =	0.000
Q/T =	0.000
M2/A =	0.072
M3/A =	-0.004
Isovist form-factor =	1.209
BME form-factor =	1.400
Gross Free Area (GFA) =	0.270

Figure 51





ISOVIST file PIE895
BME file BEND95

Un-rotated position.

Isovist Area (A) =	21.420	Variability (lamda) =	0.313
Total Perimeter (T) =	19.201	Compactness (C) =	15.455
Occlusive perimeter(Q)=	0.000	Circularity (N) =	1.231
Visible Perimeter (P) =	18.201	Q/P =	0.000
R-min =	0.600	Q/T =	0.000
R-max =	4.718	M2/A =	0.091
R-mean =	2.205	M3/A =	0.059
Standard Deviation =	1.399	Isovist form-factor =	1.063
Variance (M2) =	1.956	BME form-factor =	1.317
Skewness (M3) =	1.232	Gross Free Area (GFA) =	0.619

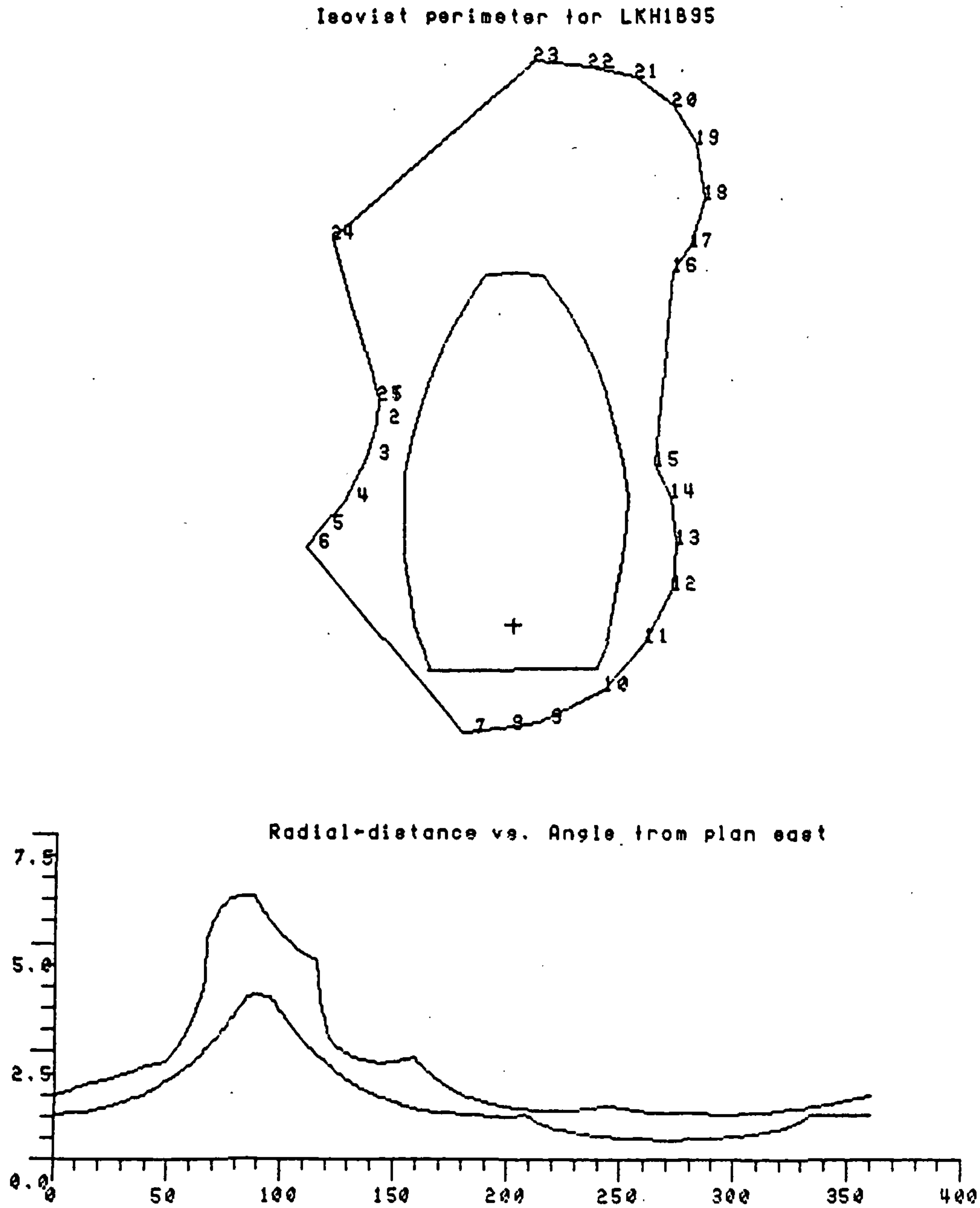
Figure 52

measures for the Boeing-Lockheed and Lockheed 1 spaces of equal area offer insight into how complexity of form may effect kinesthetic habitability.

Insert Figures 53 thru 58

The nearly square Boeing-Lockheed space offers regularity and simplicity in contrast to the irregularity of the dual-chambered Lockheed 1 space. The more compact, regular square shape boasts a higher KE and lower PAI and QOI measures. These advantages may be seen as the result of an area which is more accessible to the bme because of the simple linear nature of its surrounding surfaces.

The cost of this enclosure feature is indicated by the space's inability to accommodate the more elongated Reach 95 bme. Even though much more of the area of the Lockheed 1 space is inaccessible to the bme's, the overall conformity of shape is better. That is, the more elongated space better accommodates the elongated bmes. Even though in some ways the Lockheed 1 space may seem more restrictive (having for example, a higher PRI and lower KE), the ability to accommodate the longer bme without requiring adaptation should be given top priority. The better KE, PRI, & QOI indicators of the Boeing-Lockheed space have been achieved at the cost of a 10% adaptation index for the Reach 95 bme. The figures also show that, although a better conformity was achieved with the Lockheed 1 shape, it was still far from optimum in accommodating the long- and smooth-lined bmes. The side chambers cannot be justified by ISOKIN analysis alone (but may be important for isovist or social logic reasons).



ISOVIST file LKH1B95
BME file BEND95

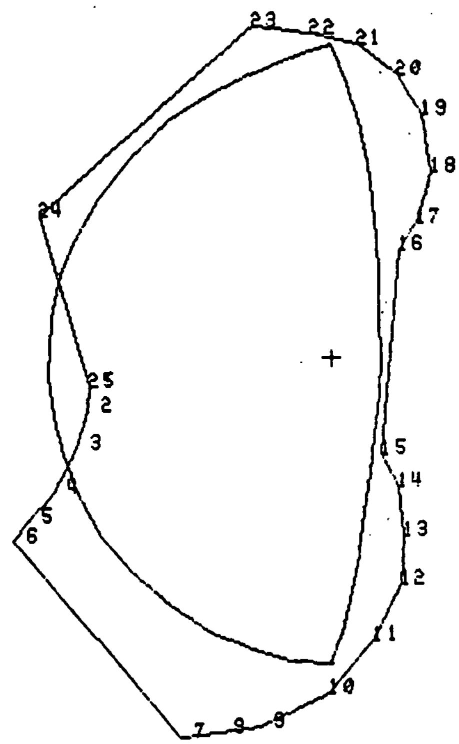
Isovist Area (A) =	21.155
Total Perimeter (T) =	19.947
Occlusive perimeter(Q)=	0.535
Visible Perimeter (P) =	18.413
R-min =	1.042
R-max =	6.060
R-mean =	2.148
Standard Deviation =	1.450
Variance (M2) =	2.103
Skewness (M3) =	4.881
Gross Free Area (GFA) =	0.614

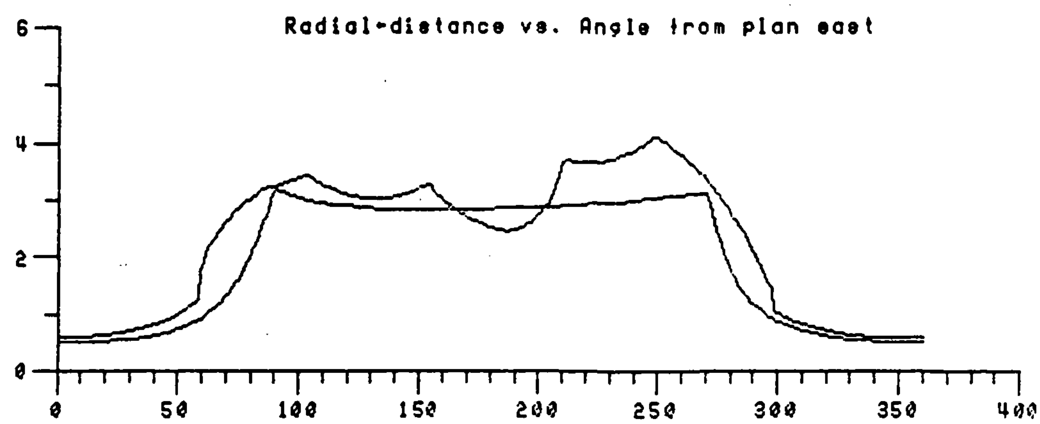
Un-rotated position.

Variability (lamda) =	0.919
Compactness (C) =	16.970
Circularity (N) =	1.350
Q/P =	0.029
Q/T =	0.029
M2/A =	0.099
M3/A =	0.231
Isovist form-factor =	1.379
BME form-factor =	1.317
Gross Free Area (GFA) =	0.614

Figure 53

Isovist perimeter for LKH1R95



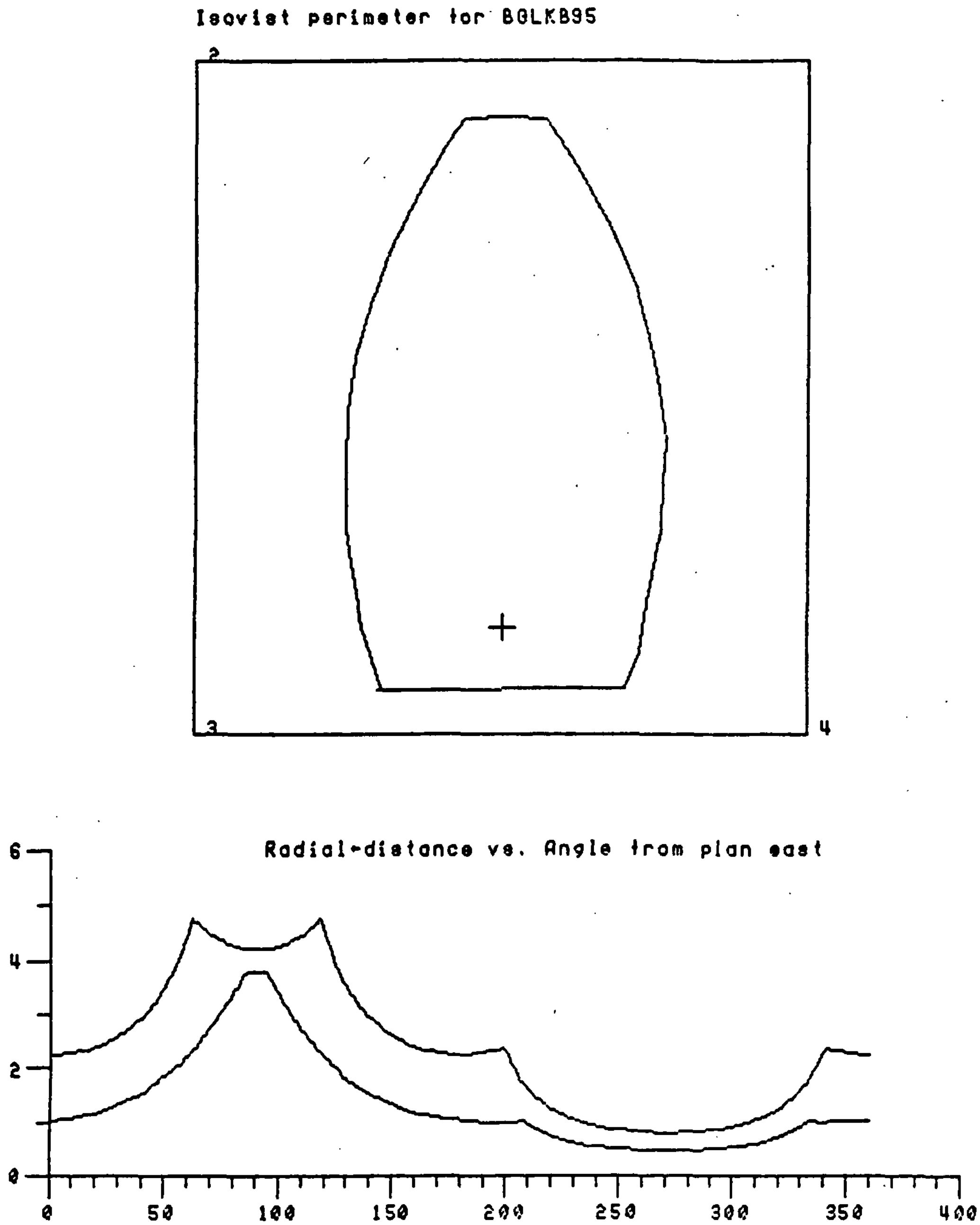


ISOVIST file LKH1R95
BME file REACH95

Un-rotated position.

Isovist Area (A) =	21.155	Variability (lamda) =	1.197
Total Perimeter (T) =	19.947	Compactness (C) =	16.970
Occlusive perimeter(Q)=	0.705	Circularity (N) =	1.350
Visible Perimeter (P) =	19.243	Q/P =	0.039
R-min =	0.583	Q/T =	0.037
R-max =	4.123	M2/A =	0.068
R-mean =	2.301	M3/A =	-0.027
Standard Deviation =	1.199	Isovist form-factor =	1.312
Variance (M2) =	1.437	BME form-factor =	1.439
Skewness (M3) =	-0.580	Gross Free Area (GFA) =	0.295

Figure 54



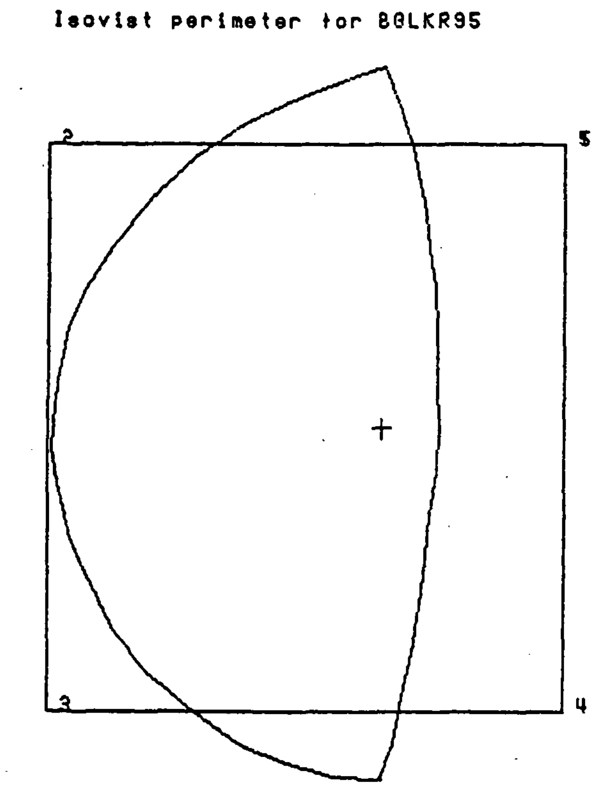
ISOVIST file B0LKB35
BME file BEND95

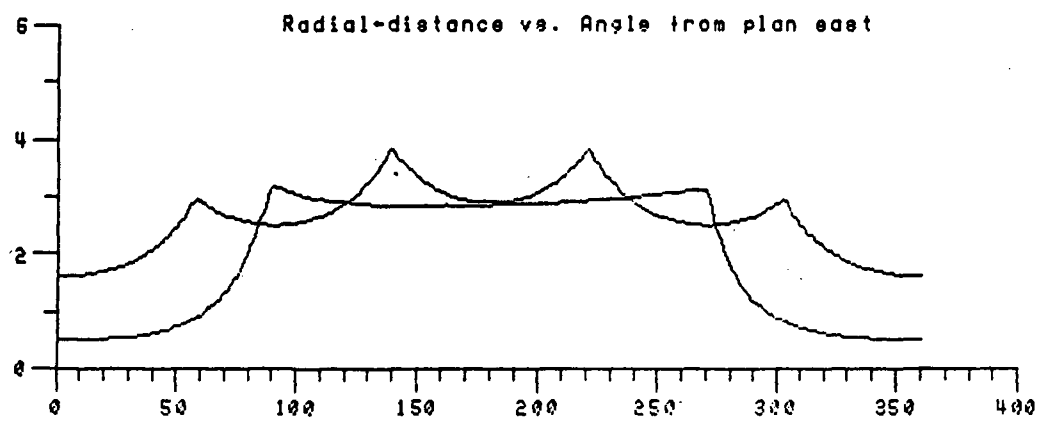
Isovist Area (A) =	22.500
Total Perimeter (T) =	19.000
Occlusive perimeter(Q)=	0.000
Visible Perimeter (P) =	19.000
R-min =	0.800
R-max =	4.757
R-mean =	2.373
Standard Deviation =	1.238
Variance (M2) =	1.532
Skewness (M3) =	0.768

Un-rotated position.

Variability (lamda) =	0.894
Compactness (C) =	16.944
Circularity (N) =	1.277
Q/P =	0.000
Q/T =	0.000
M2/A =	0.068
M3/A =	0.034
Isovist form-factor =	1.058
BME form-factor =	1.317
Gross Free Area (GFA) =	0.637

Figure 55





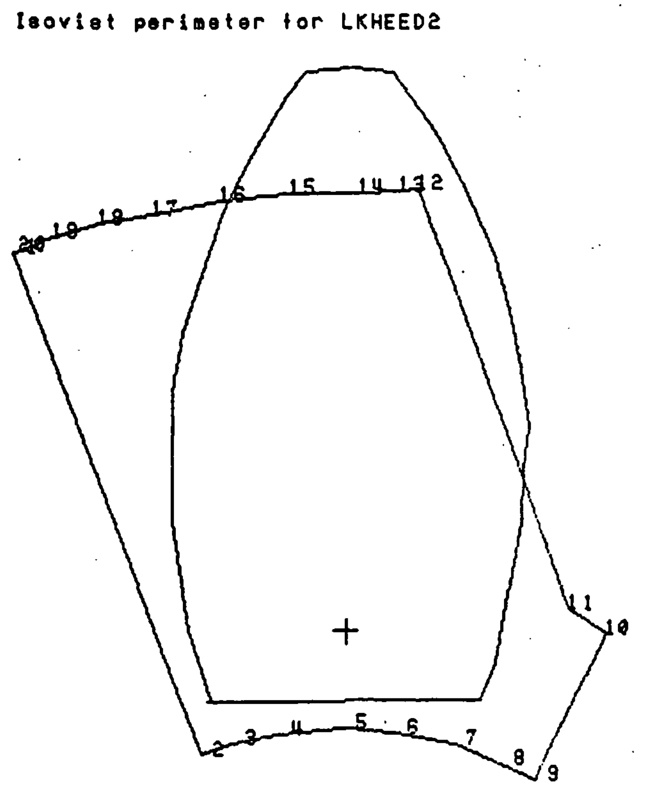
ISOVIST file BGLKR95
BME file REACH95

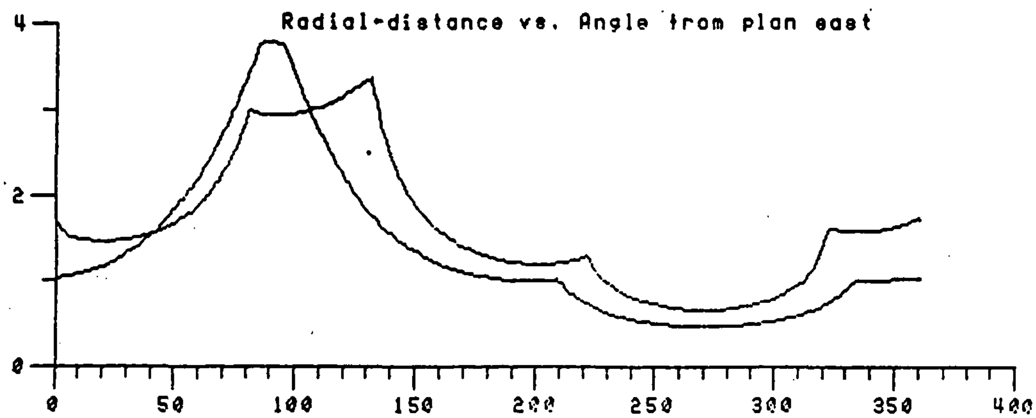
Isovist Area (A) =	22.500
Total Perimeter (T) =	19.000
Occlusive perimeter(Q)=	0.000
Visible Perimeter (P) =	19.000
R-min =	1.600
R-max =	3.911
R-mean =	2.614
Standard Deviation =	0.574
Variance (M2) =	0.323
Skewness (M3) =	-0.036
Gross Free Area (GFA) =	0.300

Un-rotated position.

Variability (lamda) =	1.328
Compactness (C) =	15.044
Circularity (N) =	1.277
Q/P =	0.000
Q/T =	0.000
M2/A =	0.015
M3/A =	-0.002
Isovist form-factor =	1.108
BME form-factor =	1.401
Gross Free Area (GFA) =	0.300

Figure 56





ISOVIST file LKHEED2
BME file BEND95

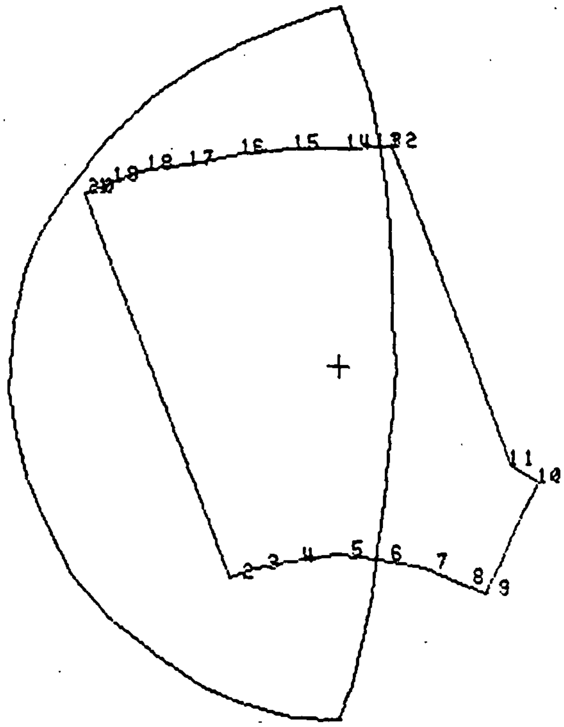
Isovist Area (A) =	10.058
Total Perimeter (T) =	13.027
Occlusive perimeter(O) =	0.000
Visible Perimeter (P) =	13.027
R-min =	0.651
R-max =	3.361
R-mean =	1.619
Standard Deviation =	0.763
Variance (M2) =	0.582
Skewness (M3) =	0.350
Gross Free Area (GFA) =	0.188

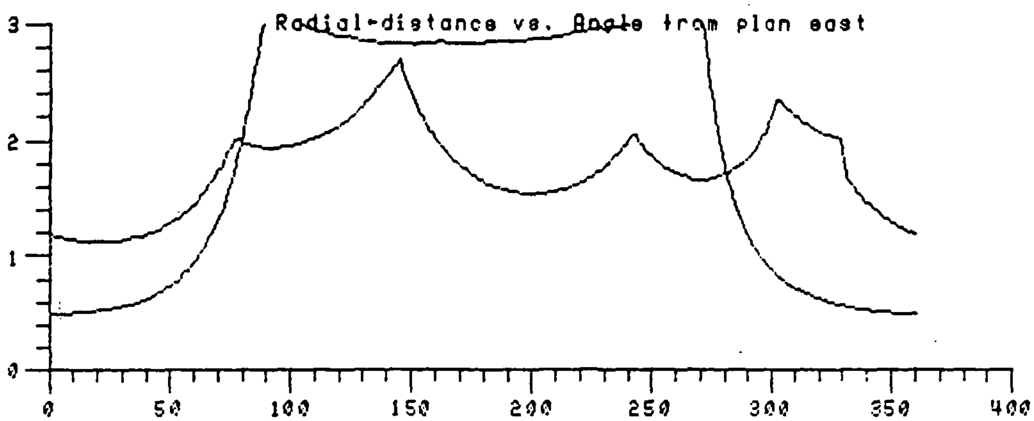
Un-rotated position.

Variability (lamda) =	0.371
Compactness (C) =	16.872
Circularity (N) =	1.343
O/P =	0.000
O/T =	0.000
M2/A =	0.058
M3/A =	0.035
Isovist form-factor =	1.216
BME form-factor =	1.317
Gross Free Area (GFA) =	0.188

Figure 57

Isovist perimeter for LKHEED2





ISOVIST file LKHEED2
BME file REACH95

Un-rotated position.

Isovist Area (A) =	10.058	Variability (lamda) =	1.274
Total Perimeter (T) =	13.027	Compactness (C) =	16.872
Occlusive perimeter(Q)=	0.294	Circularity (N) =	1.343
Visible Perimeter (P) =	12.733	Q/P =	0.023
R-min =	1.115	Q/T =	0.023
R-max =	2.696	M2/A =	0.014
R-mean =	1.749	M3/A =	0.000
Standard Deviation =	0.377	Isovist form-factor =	1.321
Variance (M2) =	0.142	BME form-factor =	1.409
Skewness (M3) =	0.004	Gross Free Area (GFA) =	-0.546

Figure 58

The Lockheed 2 space has a proposed 50% reduction in area as compared to the Boeing-Lockheed and Lockheed 1 spaces. The GFA reduction is so extreme that neither the bend nor reach bmes may be accommodated in their preferred position without adaptation. There is one position of the bend bme that can be accommodated and results in efficient use of the space though at the cost of location variability in space use. The tradeoff illustrated here is a central issue in the design of efficient and habitable spaces. It is theoretically possible to design the spaces to accommodate all required bmes in only one position and achieve a very high (100%) kinesthetic efficiency and conformity. However, the loss of position variability in the highly specialized space may severely reduce perceived habitability.

It is clear from those examples that no one ISOKIN measure alone can predict the overall worthiness of a space for specific bmes. Rather, some weighted summation of these measures must be considered. This requires both a complete inventory of unconstrained bmes that need accommodation and some clear value policy about the relative desirability of locational and behavioral variety.

Concluding Comments on Isokin Analysis

ISOKIN analysis shows that it is possible to operationalize and measure formerly intuitive notions about how spaces influence behavior. In the relatively limited simulations we have attempted, certain costs and tradeoffs of tight spaces have already become apparent.

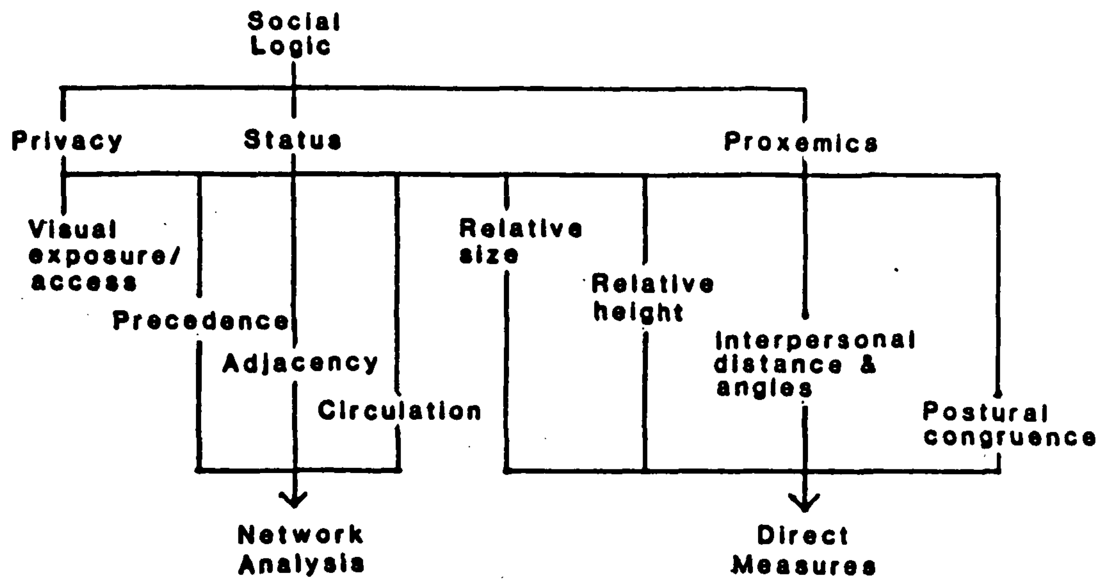
Tight spaces limit both the variety of activities and the variety of places in which those activities can be performed. As the size of a space decreases, however, these constraints are not equally expressed. The nature of constraint appears to depend on the form of the bme relative to the form of the enclosure. If the form factors are very different, adaptations to the bme will be more significant for a given size surround; but an adapted bme may be able to take place at more positions in the space. Compactness is the important consideration when working with form factors. For example, if the enclosure is more compact (say circular), then the relative differences in form (i.e., CI) are less important (once adaptation has occurred.) On the other hand, if the bme is more compact, adaptation will most likely not be required and position variability is less constrained. If the form factors are similar, the activity described by the bme will require less adaptations; but the positions in the space where it can take place are greatly reduced. The luxury of spaces that are large relative to the activities they enclose is that the activities can show variety in both form and place.

Using ISOKIN analysis, it is not possible to decide, prima facie, which size and shape spaces would be the best for a given general function--private crew quarters, for example. First, the range and type of activities to be enclosed must be specified, and then these must be ordered in terms of their adaptability to spatial limitation and their replicability at other points within the station. Once these admitted value judgments are made, ISOKIN analysis can determine which enclosures best accommodate the required activities.

Because elongated and compact spaces efficiently accommodate different, but potentially equal valued aspects of behavioral variety, we suspect that it is unlikely that the general optimum design for a private crew quarter will be a simple, or regular, form. The most space-efficient design will combine aspects of compactness and elongation into a more complex form specifically sized for the required bme's. Some of the crew cabin proposals illustrated here demonstrate this bivalent capability.

Based on preliminary and limited simulations of spaces, another conclusion is suggested. The minimal volume of an enclosed crew cabin should not be less than 150 ft^3 if satisfactory kinesthetic habitability is to be maintained. Our simulations at 105 ft^3 all showed significant shortcomings for simple dressing motions' bmes of 95th-centile males, and it would seem that this is a daily activity that should be commodiously supported. It is hard to imagine some clever design that would arrange the needed space while using less than 150 ft^3 of it. Similarly, it would seem that a 200 ft^3 assignment would solve the problems too inefficiently. We estimate that further, more detailed study will result in cabin enclosures between 150 ft^3 and 180 ft^3 that, from a kinesthetic perspective at least, are ideally suited to the activities required of them.

SOCIAL LOGIC



Introduction

We view soical logic as another, qualitatively different aspect of human spatial habitability. The term "Social Logic" is borrowed from Hillier and Hanson's (1984) text, The Social Logic of Space. In their book, these authors describe "how spatial organization is in some sense a product of social structure." They set out to find the elementary structures of human spatial organization, to represent these, and to show how they relate to make a coherent system of spatial usage. The level of scale here is with town and city planning, but another architect (Stansall 1985) has shown that their program may be used to analyze spaces within buildings as well. At the root of social logic lies the recognition that spaces carry social messages frought with meaning for their inhabitants--messages that are encoded in the physical arrangement.

Hillier and Hanson (1984) see two fundamental principles at work in establishing social logic. The first of these is <u>convexity</u>. It describes how, and how much, space is enclosed. The second is <u>axiality</u>. It describes how and where a space is connected to other spaces. The patterns of enclosure and connection are co-determined as much by the societal rules and conventions as they are by landform or ambient characteristics. They display a "social logic."

Illustrative examples of social logic are often found in indigenous cultures, where certain directions are sacred, certain connections, taboo. Women or young males may be required to live apart, and the enclosure and connectivity of their dwelling spaces reflect the established social order.

Similar instances of social logic, both equal and less formal, occur in any modern office building. Upper-level executives are given more enclosed space (private offices) in the corners on higher floors where they are accessed (connected) only through a private secretary. "Social Power" in an office landscape, as described by Lipman et al. (1978) can accrue through an opportune placement of a clerk's workstation at the corner of a corridor, which allows casual monitoring of personnel movements.

So there is more to spatial habitability than its visual appearance or the kinesthetic restrictions on body movements. A space becomes more livable, more fit for habitation, if it also reflects the appropriate rules of social order and interaction. The social logic expressed by a habitable space must be congruent to the social rules of human organization.

Components of Social Logic

The social logic of space and the social criteria it responds to are akin to form and content. Each reflect the other, and each can serve as a starting point for a structural analysis. One can take convexity and axiality and show how these spatial descriptors respond to social requirements. Or, one can take the requirements and see what sort of spatial demands are manifest.

The structural model that we developed takes the latter approach and begins with three highly salient social criteria. These are the needs for privacy, status, and the complex of spatial controls on interpersonal communication, which is called proxemics. This is not to say that these are the only demands worth considering.

A recent STS flight crew member confronted the religious question of "which direction to pray toward Mecca" when one is in orbit . ('Down' ruled the Mullah--which in fact is "up" within the 1-g reference orientation of the shuttle interior when its payload bay doors are open toward Earth.) There will certainly be other, perhaps more pernicious problems in the future, as multicultured crews are flown. But privacy, status, and proxemics concerns cover a lot of social territory and serve as good examples of how volume and geometry can act to serve or obstruct the enclosed social processes.

Privacy

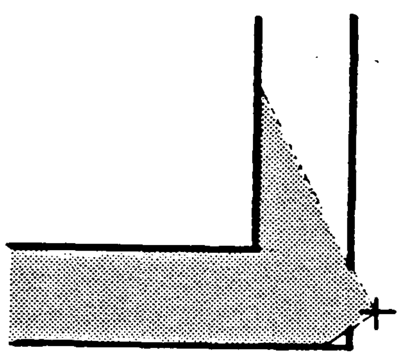
Privacy is being treated in a separate NASA study currently underway (Harrison and Sommer 1986) which reviews the considerable literature on this topic. Our purpose here is to briefly outline some of the spatial implications of that work and to show how these can be analyzed in terms of quantitative analogues of convexity and axiality. Again, these appear to be, in part, surprisingly similar to the techniques of isovist and isokin analysis previously presented.

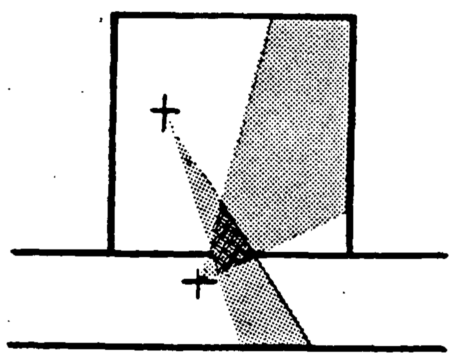
Privacy, in particular, can be thought of as an interpersonal boundary control process that either restricts or exposes information about oneself (Altman 1975). While such information can be communicated (and received) through any of our five senses, the most relevant concern for the volume and geometry of a habitat is visual privacy. Visual privacy is most commonly gained through enclosure, which in turn manifests the "convexity" principle. As any occupant of open-plan offices knows, it is possible to have visual without sonic privacy, but when enclosing elements are surface-treated appropriately, more enclosure yields more privacy of all kinds.

An important tool for the quantitative analysis of visual enclosure has been developed by Archea (1984). He calls it the "visual access and exposure" model, but it can also be addressed in terms of isovist theory. "Visual access is the potential for monitoring one's immediate physical surroundings by sight" (Archea 1984, pg. 40). "Visual exposure is the likelihood that one's own behavior can be monitored from his/her immediate physical surrounding" (Archea 1984, pg. 309).

Spatial enclosure as well as ambient conditions combine to create both abrupt changes and gradients of visual access/exposure in any habitat. A person peeking around a corner has high visual access and low visual exposure. as does a watcher from the shadows. The glare of stagelights produces the opposite conditions, where a performer is observed, but not observing.

Isovist theory is capable of describing the spatial conditions that provide these varying combinations of visual access and exposure when the analysis is extended to multiple vantage points. Vantage points that have large areal and positively skewed isovists are those that provide high access with low exposure. Peepholes, corners, and the ends of corridors are routine physical examples.





If a position is in the areas of isovists taken at many different surrounding perspective points, that position has high visual exposure. Although isovist theory itself does not make the distinction, we know from practice that some vantage points to one's workstation, room or living space are much more intrusive on visual privacy than others. To be watched from above and behind seems particularly invasive. (It is, unfortunately, a condition found in many office settings.) Isovist theory can quantify the spatial conditions that create visual access/exposure potential. How relatively advantageous or damaging these are to individual privacy requires interpretation based on other evidence.

Wichman (1979) describes an example where a firm shifted from traditional closed to open plan offices. The earlier arrangement had allowed executives to signal their availablity to colleagues by leaving their doors slightly ajar (a system that is also common in dormitories). The new office partitions did not allow this convenience, and so informal visitors had to peek around or over the partitions to see if the occupant was busy. In his/her peripheral vision, the occupant notices the peeker, but to make eye contact with the (now) intruder is tantamount to accepting the visit. So the occupant must pretend not to notice and so feels uncomfortable and rejecting while the visitor feels overly intrusive and humiliated. The outcome here was a dramatic decline in face-to-face visits among executives, which was seriously damaging to company collegiality.

In isovist terms, the users of the setting were no longer able to manipulate visual exposure aspects of their private spaces, in order to signal social intent. Their control over surrounding vantage points diminished, along with any sense of individual privacy.

Heubach (1984) also has performed a detailed study that examined how well the visual access/exposure model describes privacy seeking in junior high school students. She found that visual exposure was a particularly strong determinant of location selection for privacy-required behaviors.

By selecting many different points in a setting, it is possible to generate an "isovist field" (Benedikt 1979) for any isovist measure one chooses. Figure 59 illustrates such an area field for a room off a hallway (Benedikt 1978). Vantage points of identical area isovists are connected to form the "visual contours" shown. Each contour connects a string of different (but equal area) isovists, much like the contours on a map connect equal but different elevation points.

Insert Figure 59

By this means, it is possible to represent different spatial configurations and determine these positions where visual access and exposure waxes and wanes. Heubach (1984) has also provided a shorthand method for computing access and exposure at selected locations. Figures 60 and 61 show how two proposed crew cabin designs succeed in giving an occupant some low visual exposure, even in a small space. In both of these, there is a useable part of the cabin that is out of view of the passageway.

Insert Figures 60 and 61

If it is desirable that crew members be able to spend some time in their cabins "off stage" and involved in their own pursuits, such an arrangement of views-in would seem necessary. If these were combined with a cabin door that could be left partially open, the means for a visual privacy control system would have been established.

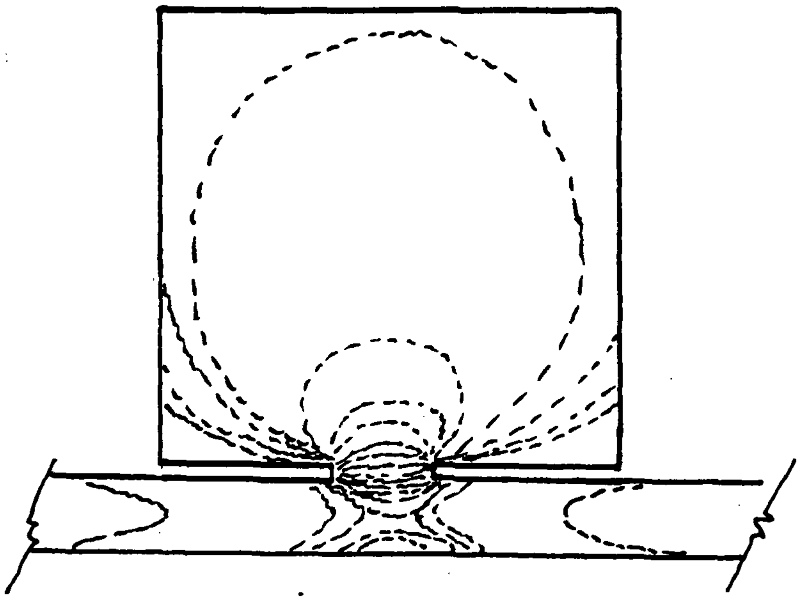


Figure 59: An Areal Isovist Field
for a Room off of a Hallway
(after Benedikt 1978)

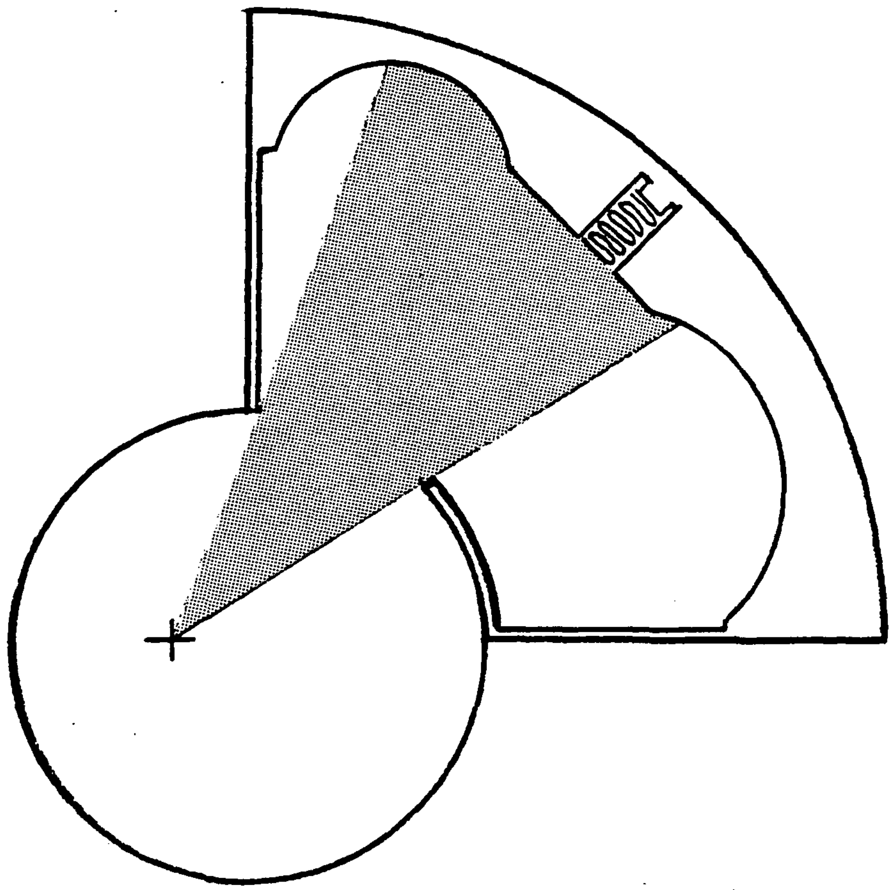


Figure 60: View Access into a Lockheed Cabin Proposal

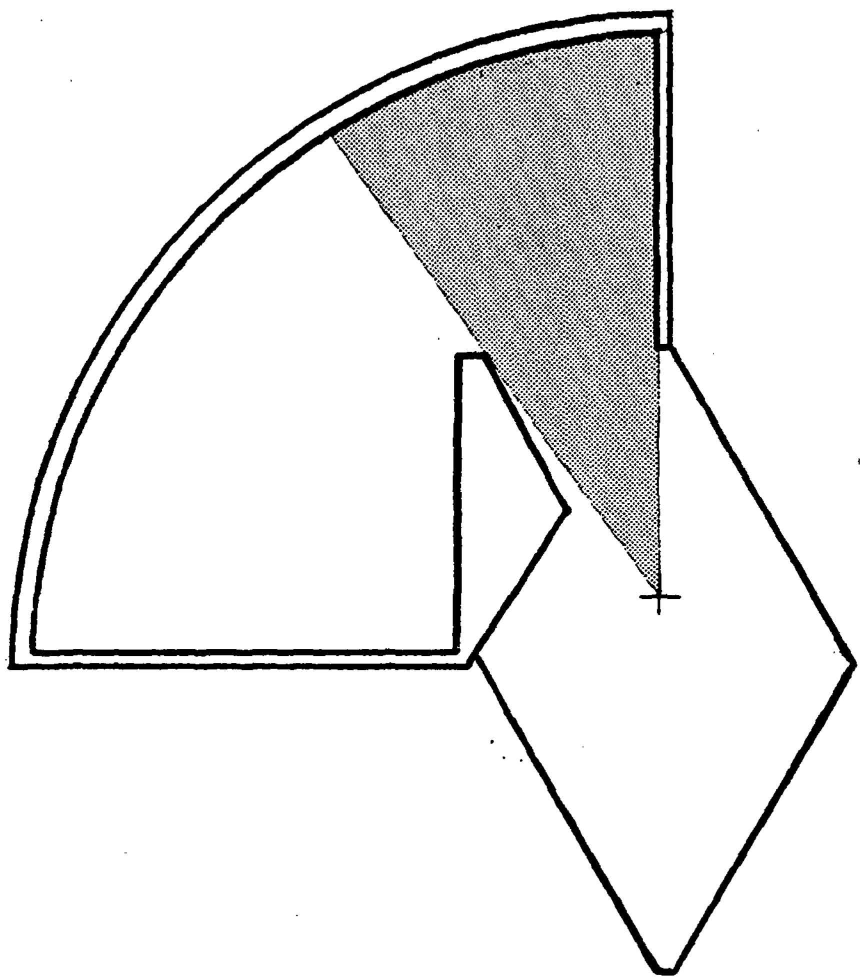


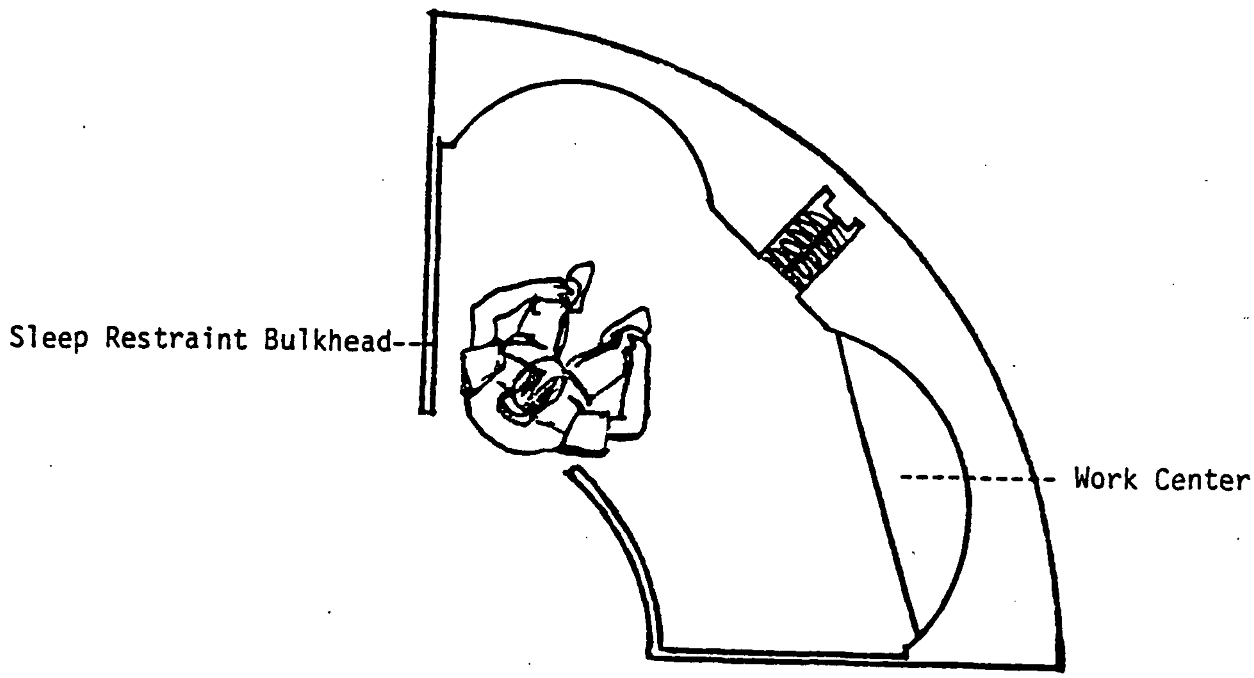
Figure 61: View Access into a Boeing SOC Cabin Proposal

Status

Of course, there are other spatial modifiers of privacy than those concerned with visual aspects. Privacy increases with the degree of necessary penetration, or number of spaces that one must pass through in order to reach a given space. This is called precedence (a manifestation of axiality). It means, generally, that our most private rooms are located furthest from entries, setting up a "privacy gradient" for any habitat. A more private apartment or condominium in a complex is one at the end of a street or corridor, where other residents will not have to pass by its door.

As a spatial device, precedence is also a strong indicant of social status. One must move through several lower functionaries to reach a high-status executive, and one must move through several spaces--anterooms and corridors--to reach the most valued (and private) room of a dwelling, say a private library.

The rule of precedence is straightforward and unvarying. Higher status people, places, things, and events come later--in both space and time. This rule applies within spaces as well as between them. In a "high-status" office, one must walk across the room from the entry in order to reach the occupant. Similarly, a bed in a master bedroom is never placed adjacent to the doorway of that space. In one of the few crew cabin proposals (see below) that separates the sleep restraint from the work/communication center, the sleep restraint is placed next to the entry, while the work center is "further" into the space. Social logic, under the criterion of precedence (an axiality condition) would reverse this ordering.



Other spatial indicants of privacy and status are concerned with adjoining and circulation. Under the adjoining rule, what is <u>next to</u> the space one occupies helps determine the exhibited social value. Under the circulation rule, there are different values ascribed to "pass through" or "pass by" arrangements.

Thus, a particular private crew quarter would be less socially valued if it were placed next to the crew's "hygiene facility" or laboratory animal cages. A space like a wardroom becomes less sociable if circulation in the habitat is directly through its middle, rather than off to one side. Parlors, dens, or living rooms in homes are not traversed in order to reach other parts of the dwelling. If this becomes necessary due to space restrictions, the passage is usually at one end of the space.

Analytically, precedence, adjacency, and circulation conditions can be handled by a branch of graph theory called network analysis. Stansall (1985) gives in-depth examples of its application to the spatial organization of offices. By this means, any floor plan can be abstractly represented, both graphically and through a binary square matrix. Figure 62 shows two floor plans, one elongated and one square, with their matrix and graphical abstractions.

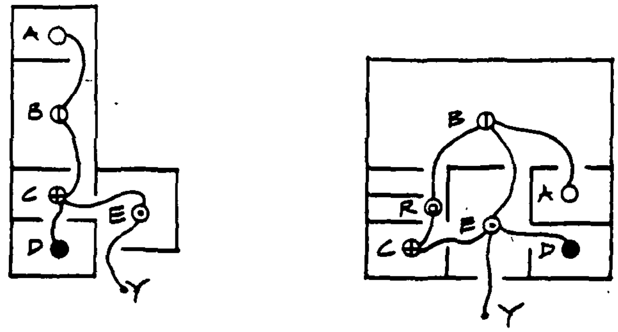
Insert Figure 62

Beginning with a floor plan, the individual spaces are lettered and designated according to function. Here CASE I and CASE II (adapted from an example by Stansall 1985) show an elongated and square floor plan, respectively. The networks on the floor plans show how the spaces connect.

First, a square binomial adjacency matrix is constructed with a '1' entered when there is a direct connection between any pair of spaces. Here a space is always seen to connect with itself.

Floor Plans

Case I **Case II**



Adjacency Matrix

	A	B	C	D	E	Y
A	1	1	0	0	0	0
B	1	1	1	0	0	0
C	0	1	1	1	1	0
D	0	0	1	1	0	0
E	0	0	1	0	1	1
Y	0	0	0	0	1	1

	A	B	C	D	E	R	Y
A	1	1	0	0	0	0	0
B	1	1	0	0	1	1	0
C	0	0	1	0	1	1	0
D	0	0	0	1	1	0	0
E	0	1	1	1	1	0	1
R	0	1	1	0	0	1	0
Y	0	0	0	0	1	0	1

First Order Reachability Matrix

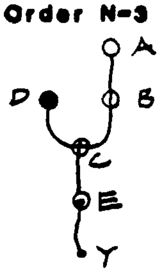
	A	B	C	D	E	Y
A	1	1	1	0	0	0
B	1	1	1	1	1	0
C	1	1	1	1	1	1
D	0	1	1	1	1	0
E	0	1	1	1	1	1
Y	0	0	1	0	1	1

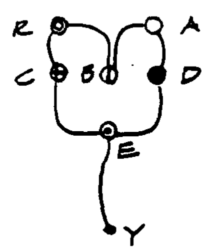
	A	B	C	D	E	R	Y
A	1	1	0	0	1	1	0
B	1	1	1	1	1	1	1
C	0	1	1	1	1	1	1
D	0	1	1	1	1	0	1
E	1	1	1	1	1	1	1
R	1	1	1	0	1	1	0
Y	0	1	1	0	1	0	1

• ← **Second Order** → •

• ← **Third Order**

Reachability Order N=3 **Reachability Order N=2**





Case I **Case II**

Figure 62: Network Analysis for Two Alternate Floorplans

But spaces don't only connect, they "reach" each other through intermediate spaces. A first order reachability matrix is easily computed by multiplying the adjacency matrix by itself. The new entries of '1s' in the matrix now indicate which spaces are reached through one intermediary space. For example in CASE I, A reaches C through B, but in CASE II, this will not happen until second-order reachability. Successive powering operations on the adjacency matrix establish successive orders of reachability until no new '1s' are obtained.

The utility of the reachability matrix is that it can be used to develop a hierarchical digraph, which here displays the spaces in terms of their distance from the outside, indicated as Y. The hierarchical digraph also reveals the precedence relations in the floor plan which could be used to determine congruency between organizational structure and habitat layout. Of course, it is also possible to work in the reverse direction. If a set of reachability goals were set for an organization, a floor plan (perhaps several) can be derived that satisfies them.

The point is that the demands social logic makes upon precedence, adjacency, and circulation can be represented and analytically compared in any set of alternative facility (or space station) layouts. In the two Cases presented, the average number of spaces that each space is apart from any other space is 1.53 for CASE I and .95 for CASE II. This is an index of the integration of the facility (Stansall 1985).

For a hypothetical space station layout, it should be possible to construct different hierarchical digraphs to see how alternate configurations perform with respect to reachability from different nodes, such as airlocks, ward-rooms, or safe havens. The overall performance of alternative layouts with respect to such locational criteria, be they derived functionally or through appeal to social logic are not always evident or immediately comparable. Network analysis is a useful tool for operationalizing what has long been the province of architects' educated intuition.

Proxemics

Proxemics is the study of space as a communications medium. Proxemic relationships play an ongoing part of every social encounter, although many of these are so well learned by people that they go virtually unnoticed. In social situations, individuals maintain mutual and reciprocal control over spatial quantities such as interpersonal speaking distance, relative heights, and orientation of parts of their bodies (Bull 1983). The nonverbal silent cues sent by spatial displays in social communication significantly determine how the overall message is perceived and interpreted.

To date, the proxemic qualities of living in close quarters under microgravity have not yet been systematically studied, even though a rich data source is available in videotapes and movies of Skylab and STS missions. However, anecdotal evidence indicates that earthbound proxemic mechanisms are readily transferred to space habitats (Cooper 1976; Pogue 1985).

Skylab astronauts would not float over their dining table to reach food storage bins, just as one does not reach or jump across a dining table in an earthbound residence. Astronauts also maneuver themselves into a similar "personal vertical" to carry on conversations, and have sometimes requested this of their colleagues. Reading facial expressions is equally important for communication, regardless where it takes placeThe proxemic implications for volume and geometry guidelines are both immediate and important for designing in the social logic of a habitat.

Generally, the space available, and the configuration of that space, should allow for the relatively unconstrained exercise of proxemic control mechanisms. This means that:

a. When a conversational or social recreation space is indicated, the space should be configured so that n individuals can occupy it with inter-personal speaking distances of from 1.5 to 4.0 ft. at approximately 90^0 to120^0 angles from each other. In American culture, 90^0 (around a corner) is the preferred angle for casual conversation, while 180^0 (across) is selected for competitive games or negotiations.

b. Equal relative heights among social conversants should be maintained through spatial configuration and the placement of fixed or ad hoc positioning restraints. This is because, unequivocally, significant differences in relative height, either real or symbolically implied, carry strong connotations of social power and dominance. The higher status person always stands on a podium or sits in a high-back chair, occupying a greater relative height.

Relative height in particular has strong implications for the design of social recreational space within a cylindrical habitat. Here, there is a great temptation to increase space efficiency by going "up" an imposed vertical bulkhead to create more restrained positions. While it may be acceptable practice to allow such variety of positioning, it is probably not advisable to impose strong relative height differentials as the <u>only</u> way of fitting a given number of people in a space. The social dominance message here is likely to be particularly enduring and generalized across expected crew cultures.

c. Restrained rest positions should allow conversants to maintain "postural congruence" (Scheflen 1964). This means that, in a socially communicating group, it should be possible for all to position themselves in relatively similar styles of body orientation and limb location, and in mirror congruence. Similar or congruent postures appear to be an indicant of rapport and agreement within a group. If postural attitudes thusly correspond to social attitudes, it would seem prudent to design so that expression of this proxemic mechanism becomes possible. Again, allowing exercise of established spatial communication habits can only enhance the habitability of a confined environment.

Unlike some of our earlier presented models of visual spaciousness and movement analysis, proxemic research shows a rich history of testing and application. Bull (1983) and Altman (1975) provide exceptional overviews of this literature, while Evans (1982) examines the relationship of proxemic (and other) coping mechanisms to environmental stress.

Concluding Comments on Social Logic

The social logic of space operates in terms of privacy and status gradients, social power, and interpersonal perception, all of which are communicated by how spaces are sized, bounded (convexity) and connected (axiality). Spatial messages are almost always interpreted relative to their context. Size of an assigned workspace carries meaning not in absolute terms, but in terms of the sizes of one's colleagues' workspaces; its placement relative to others signals the social or functional worth of the occupant's role in the organization.

To analyze a space station habitat in terms of social logic first requires a clear social and organizational philosophy. How is a crew to be organized and led? A military type model has far different implications for the social design of habitat than does one based on "matrix management."

For example, it would probably be unavoidable that in a "hotdog" model of space allocation within a cylinder, a linear arrangement of private crew cabins would result in one end being "more preferred" than another. This may result from proximity to a hygiene station, commander's cabin, or even a safe haven. This immediately would set up an imposed status hierarchy which may work against actual crew management. "Revolver" type models of crew cabin arrangements sidestep the potential nicely, perhaps at the functional cost of congested egress into a single central passageway.

It is not uncommon to find that social logic is sometimes at conflict with the functional needs of spaces. In businesses, executives may have the best chairs and the best views, when they actually spend little time behind their desks. Here, a greater need, a social one, is being fulfilled. Any organization must somehow grapple with the respective worths of spatial allocation and arrangement, deciding which facility supports of individual, organizational, and social functions create a "best fit" to its raison d'etre. The proposed station is no exception, and its ability to reflect the social logic that NASA deems most desirable for its successful operation will undoubtedly be an important contribution to its overall spatial habitability.

CONCLUSIONS

In this study, human spatial habitability was conceived and operationalized in terms of three major aspects. These were called its VISUAL , KINESTHETIC, AND SOCIAL LOGIC components. Each of these was decomposed in turn to a limited set of bottom line measures purported to capture the relevant environmental effects of living in tight spaces.

Although these aspects of spatial habitability were presented independently, in practice the contributions of conditions represented by their measures combine to operate in a wholistic sense. Visual spaciousness, available body motion envelopes, and the observance of a subtle yet pervasive social logic concatenate to produce what we experience as a habitable space. One part of the experience frequently affects another, even if there is no immediate and direct physical reason. So Savinar (1975) found that increased ceiling height reduced feelings of crowding, even though floorspace remained constant. In our terminology, increasing the volume of the isovist affects one's appreciation of available activity space and how this is occupied by others. The interdependent linkage here lies in the perceptual/motor systems of the observer/actor, not in any physical necessities of the space.

This is both good and bad news for the modelling (and the application of models) of spatial habitability. Recognized interdependencies are useful because they allow a designer to solve problems in a variety of ways. If physical space is at a premium, then visual space can be made to substitute for it, at least in part.

However, interdependencies are problematic, because they imply that the goals of design cannot be neatly categorized into different parts of a checklist , and then ticked off as a subset of conditions are satisfied. This is what makes it impractical (and impossible) in our estimation, to present some algorithm of a general model of spatial habitability which would provide a recipe for the ideal space along with the weighted importance of the various ingredients.

The dimensions of habitability are integral, not componential, and each of our "aspects" of habitability should be designed in to its fullest in order to ensure the level of habitability that a space station demands. Even the word "level" here is misleading if it implies that one could put together a facility according to increasing orders of livability. It is much more of an all-or-none case, where design intentions must be constantly reaffirmed on all levels of detail if they are to be manifest in occupants' experiences. A habitable space is a pattern of effects, not a laundry list of conditions to be satisfied.

Fortunately, a distinction can be made between the performance criteria that describe habitability and the physical manipulations that produce it. Our modelling and background research has emphasized attention on performance criteria rather than explicit forms so that the lessons of this study would have a wide range of practical applicability.

For example, if one wants to specify a small, enclosed volume that looks as large as it can or larger than it is to an occupant, one should do the following:

Select some preferred vantage points within the volume and shape the space so as to maximize the area and variance of the isovist from these points. It is also suggested (but not confirmed) to shape the space so that lambda (sequential irregularity) is low from the same vantage points. These criteria devalue compact or very regular spaces, since these have a lower variance in their isovists from corresponding points. For equal-sized small volumes, elongated shapes show enhanced visual spaciousness.

Kinesthetically, however, compact spaces are often more efficient, and they are also likely to show more rotational accommodation of body motion envelopes. So it is reasonable that there may be a conflict in the minimal space requirements set by visual and kinesthetic considerations. But whether a proposed cabin should be chosen on its visual or kinetic bases ought not to be an issue. With a clear understanding of the physical motions to be enclosed, a cabin design should be possible that achieves both visual and movement habitability criteria.

Although spaces act as "whole systems" in terms of their livability, analyzing them partwise in terms of qualitatively different performance criteria does allow a design to successively "come into form" (Alexander 1966). The process needs to be one of first seeing what form each set of criteria is trying to express and then finding an acceptable solution in the union of these possibilities. This is part the science and part the art of engineering design.

The most important conclusion of this study is that it is possible to operationalize and apply the intangibles of spatial habitability, much as it is possible to apply hard engineering criteria. Although empirical work needs to be done to determine the relative contributions of different parameters, the models presented here at least seem to abstract and represent the useful quantities that mediate between space enclosures and how these are sensed by their inhabitants. The human factors of spatial habitability deserve an equivalent role in space station design to that held by more traditional engineering and life support considerations.

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