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From space syntax to space semantics: a behaviorally and perceptually oriented methodology for the efficient description of the geometry and topology of environments

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Abstract. Human spatial behavior and experience cannot be investigated independently from the shape and configuration of environments. Therefore, comparative studies in architectural psychology and spatial cognition would clearly benefit from operationalizations of space that provide a common denominator for capturing its behavioral and psychologically relevant properties. This paper presents theoretical and methodological issues arising from the practical application of isovist-based graphs for the analysis of architectural spaces. Based on recent studies exploring the influence of spatial form and structure on behavior and experience in virtual environments, the following topics are discussed: (1) the derivation and empirical verification of meaningful descriptor variables on the basis of classic qualitative theories of environmental psychology relating behavior and experience to spatial properties; (2) methods to select reference points for the analysis of architectural spaces at a local level; furthermore, based on two experiments exploring the phenomenal conception of the spatial structure of architectural environments, formalized strategies for (3) the selection of reference points at a global level, and for (4), their integration into a sparse yet plausible comprehensive graph structure, are proposed. Taken together, a well formalized and psychologically oriented methodology for the efficient description of spatial properties of environments at the architectural scale level is outlined. This method appears useful for a wide range of applications, ranging from abstract architectural analysis over behavioral experiments to studies on mental representations in cognitive science.

1 Introduction

The form and configuration of architectural space influence experience and behavior. When, for example, people enter an empty restaurant, they do not sit down at an arbitrary place, but carefully choose a seat in relation to the surrounding architectural features (Robson, 2002). Likewise, when looking for specific places in unfamiliar environments, movement decisions during exploration contain regular patterns that appear to be induced by the shape and configuration of the spatial environment as well as by visuospatial characteristics of decision points (cf, for example, Janzen, 2000; Zacharias, 2001). Indeed, influences of selected features of spatial situations on human behavior have been investigated in numerous studies. For example, O'Neill (1992) has demonstrated that wayfinding performance decreased with increasing floor plan complexity, and Wiener et al (2004) have revealed an influence of environmental regions on spatial learning, navigation, and route-planning behavior. Also, several theories from environmental psychology, such as 'prospect and refuge' (Appleton, 1988) or the framework of Kaplan (1987), explain human behavior and experience as being contingent upon features of the environment, both within and beyond a given sensory horizon.

While the truth of the initial statement is therefore hardly disputable, it remains difficult to apply individual findings for the prediction of real-world behavior, mainly

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because, in reality, various potentially relevant factors coexist. In order to obtain better predictions under such complex conditions, either a comprehensive model or at least additional knowledge on the relative weights of individual factors and their potential interactions is required. As an intermediate step towards such more comprehensive approaches, existing theories have to be formulated qualitatively and translated to a common denominator.

In this paper an integrative framework for describing the shape and structure of environments is outlined that allows for a quantitative formulation and test of theories on behavioral and emotional responses to environments. It is based on the two basic elements *isovist* and *place graph*. This combination appears particularly promising, since its sparseness allows an efficient representation of both geometrical and topological properties at a wide range of scales, and at the same time it seems capable and flexible enough to retain a substantial share of psychologically and behaviorally relevant detail features. Both the isovist and the place graph are established analysis techniques within their scientific communities of space syntax and spatial cognition respectively. Previous combinations of graphs and isovists (eg Batty, 2001; Benedikt, 1979; Turner et al, 2001) were based on purely formal criteria, whereas many place-graph applications made use of their inherent flexibility but suffered from a lack of formalization (cf Franz et al, 2005a). The methodology outlined in this paper seeks to combine both approaches by defining well-formalized rules for flexible graphs based on empirical findings on the human conception of the spatial structure.

In sections 3 and 4, methodological issues of describing local properties on the basis of isovists are discussed. This will be done on the basis of recent empirical studies that tested the behavioral relevance of a selection of isovist measurands. The main issues are (a) the derivation of meaningful isovist measurands, based on classic qualitative theories from environmental psychology, and (b) strategies to select reference points for isovist analysis in environments consisting of few subspaces.

Sections 5 and 6 then discuss issues arising when using an isovist-based description system for operationalizing larger environments consisting of multiple spaces: (c) on the basis of an empirical study in which humans identified subspaces by marking their centers, psychologically plausible selection criteria for sets of reference points are proposed and formalized; (d) a strategy to derive a topological graph on the basis of the previously identified elements is outlined.

Taken together, a viable methodology is proposed which describes spatial properties of environments efficiently and comprehensively in a psychologically and behaviorally plausible manner.

2 Background

2.1 Isovist and visibility graph analysis

For analyzing spatial characteristics of small-scale environments or vista spaces, Benedikt (1979) has proposed *isovists* as objectively determinable basic elements. Isovists or viewshed polygons capture spatial properties by describing the visible area from a single observation point. From these polygons, several quantitative descriptors can be derived that reflect local physical properties of the corresponding space—such as area, perimeter length, number of vertices, and length of open or closed boundaries (see figure 1). Their mathematical combination leads to further integrated descriptors—for example, the quotient of area and squared perimeter can be conceived as the isovist polygon's roundness value.

In order better to describe the spatial characteristics of environmental spaces (Montello, 1993) beyond a particular observation point, Turner et al (2001) have developed *visibility graph analysis*, a technique that permits the integrative analysis of

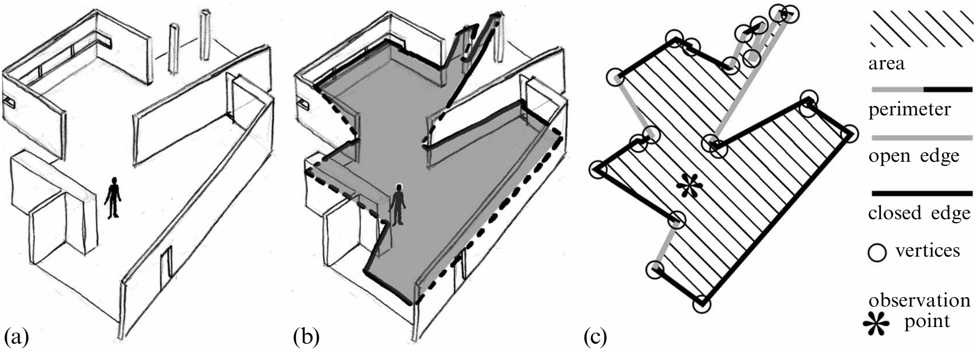


Figure 1. Generating isovists: (a) a hypothetical indoor environment; (b) the shaded area is visible from the person's observation point within the environment; (c) the resulting isovist and its basic measurands.

multiple positions within an environment by computing the intervisibility of positions regularly distributed over the whole environment. This technique offers further second-order measurands, such as visual stability (eg clustering coefficient) and, similarly to the original space syntax approach, global topology-oriented characteristics values (eg integration). A further advantage of visibility graph analysis is its bottom-up methodology—hence the analysis process can be completely automated.

While explicitly related to Gibson's (1979) theory of ecological visual perception, the behavioral relevance of these techniques was hardly backed initially by empirical findings. Meanwhile, there is first empirical evidence that isovists capture environmental properties of space relevant for spatial behavior and experience. For example, case studies on spatial behavior in the Tate Gallery (Turner and Penn, 1999) have revealed high correlations between visibility graph measurands and the statistical dispersal of visitors. Further empirical evidence of behavioral correlates to isovists is presented in section 3.

2.2 Graphs in architecture and cognitive science

In architecture, graph-like diagrams continue a long tradition of graphical analysis and have been substantially influenced by Lynch (1960). The need for strictly formalized description systems arose from the wish to perform quantitative comparisons between spatial configurations in order to identify essential properties in terms of function or usage. In this domain of *space syntax* analysis, spatial organization patterns have been seen as close parallels to the underlying social structures (Hillier and Hanson, 1984). Besides applied research, graph investigations in architecture have concentrated particularly on methodological issues, such as the transfer of analysis techniques on arbitrarily shaped environments or on variable scale levels, and on the formalization and automation of the graph generation process. Also, approaches to determine and minimize the number of necessary graph nodes have been explored (Batty, 2001; Peponis et al, 1997).

In spatial cognition and artificial intelligence, graphs have been used as models for mental representations of environments. For example, in 1979 Byrne suggested that the memory for urban environments is realized in a network of places (Byrne, 1979; see also Kuipers, 1978). Ever since, a multitude of such graph-like models of spatial memory have been developed (eg Chown et al, 1995; Leiser and Zilbershatz, 1989). The particular appeal of graph topologies as models for spatial memory arises from their superior flexibility as compared to map-like representations of space. Nevertheless, graphs allow the flexible embedding of metric information (Hübner and Mallot, 2002) and the attachment of nonspatial information, such as emotional or episodic information (Arbib and Lieblich, 1977). Also, graph structures permit the representation of inconsistencies and incomplete knowledge, factors that appear necessary to explain several empirical findings in human spatial cognition (eg Mallot and Gillner, 2000). Taken together, due to their minimalism and efficiency, graph-like mental representations of space are ecologically plausible, sufficient for the explanation of a wide range of behavior, and, last but not least, they fit well to the neural structure of human brains.

For an extensive overview and comparative analysis of graph-based models of space in architecture and cognitive science, please refer to Franz et al (2005a).

3 The derivation of isovist measurands from qualitative theories

As outlined above, the mathematical combination of a few basic isovists and visibility graph measurands results in a multitude of further description variables. The meaning and relevance of such descriptors are difficult to estimate a priori. A brute-force analytical approach is practically unfeasible, and, moreover, it severely increases the risk of producing statistical artifacts. On the other hand, cautious conservative correction methods based on the number of comparisons might completely mask effectively existing effects. Therefore, this section gives an overview on an intermediate approach that could be characterized as a theory-driven directed exploration.

Environmental psychology and normative architectural knowledge offer various qualitative theories on spatial properties affecting behavior and experience. In the following some theories are analyzed on their underlying geometrical properties and tentatively summarized. These assumed basic spatial qualities are then either related to existing isovist and visibility graph measurands from the space syntax literature, or are provisionally captured by specific mathematical combinations of basic properties. Furthermore, formal measurands described in earlier approaches of empirical aesthetics (eg Berlyne, 1972) are transferred onto isovists.

3.1 Theories on spatial qualities

Already basic adjectives describing spatial size (eg narrow, cramped, poky, spacious, ample) have strong emotional connotations. Analogously, Joedicke (1985) has suggested that the basic quality of density or *spaciousness* is an important constituent of its experience. The pathological extremes of agoraphobia and claustrophobia demonstrate that direct emotional responses to the dimension of space can be very intensive. Also, the theory of proxemics (Hall, 1966) suggests a different weighting of space according to its distance from the observer. In sum, measurands describing the mere size of available space, possibly moderated by egocentric distance, appear to capture relevant qualities of architectural space.

Related to the basic spaciousness quality, the theories of 'prospect and refuge', or the framework of Kaplan (1987), suggest preference patterns for certain configurations combining *enclosure* and openness. For example, Appleton (1988) proposed that, due to their evolution in the savannah, humans prefer environments that offer various cover and at the same time allow them to overlook other spaces.

Several theories relate affective responses to environments to perception via the computational effort required to interpret them or to encode them into spatial memory (eg Berlyne, 1972; Kaplan, 1988; Nasar, 1988). In order to describe the underlying factors, terms such as complexity, diversity, visual entropy, perceptual richness, order, legibility, clarity, and coherence have been used. All in all, there are strong indications for two main dimensions within this collection of related concepts, which may be provisionally termed *complexity* (implicating diversity, entropy, richness) and *order* (comprising legibility, clarity, coherence). While architectural theory tends to stress the aesthetic value of the latter (eg Weber, 1995), psychological experiments have rather concentrated on measuring effects of complexity.

Closely related to these static collative stimulus properties are concepts that relate to the *predictability* of an environment [eg Mehrabian and Russell's (1974, pages 75–97) 'novelty' and 'uncertainty' as part of information rate]. Also the 'mystery' theory (Kaplan, 1988) suggests behavioral and emotional responses to environments based on the expected gain of information during active exploration. The translation of predictability into formal descriptors seems, however, difficult, since its effectiveness may strongly depend on nonphysical factors such as previous exposure and familiarity. Some aspects of predictability may at least be related to similar physical properties such as the enclosure quality.

3.2 Translation of spatial qualities into isovist measurands

In the previous section four basic spatial qualities—spaciousness, enclosure, complexity, and order—were tentatively identified. Table 1 gives an overview on hypothesized connections to selected isovist measurands and their calculation methods. The basic spaciousness quality was expected to be highly correlated with isovist area (also called neighborhood size). In addition, two measurands, called 'free near space' and 'free medium space', tested for differences in the weighting of directly visible space based on its distance to the observer. Free near or medium space basically describes the proportion of a hypothetical circle around the observer having a radius of 3 m or 6 m, respectively, which would be visible.

Table 1. Summary of the hypothesized relations between basic spatial qualities and isovist measurands.

Basic spatial quality	Isovist and visibility-graph-based descriptor variables	Calculated method
Spaciousness	Isovist area	Neighbourhood size
	free near (medium) space	n visible graph vertices at 2 (4) m distance
Openness	Isovist openness	$\text{Length}_{\text{open edges}}/\text{length}_{\text{closed edges}}$
	Jaggedness	Isovist perimeter^2/area
	Revelation	(Σ area adjacent isovists − isovist area)/ isovist area
Complexity	Number of vertices	n isovist vertices, n segments
	Vertex density	n vertices/area
	Roundness	Isovist area/perimeter^2
	Jaggedness	Isovist perimeter^2/area
	Clustering coefficient	n intervisibilities within current neighborhood/ [neighborhood size × (neighborhood size − 1)]
Order	Symmetry	n symmetry axes
	Redundancy	$n_{\text{segments}}/(n_{\text{unique segments}} + 1)$

The second quality, enclosure, was seen to relate to at least two different physical aspects: the availability of vistas into adjacent spaces and the rate of accessibility. The former could probably be captured by measurands related to the convexity of isovists—such as the clustering coefficient and jaggedness—the latter simply by the physical openness ratio. Furthermore, a more behaviorally oriented measurand revelation coefficient was calculated on the visibility graph as the relative difference between the local neighborhood size and the collective neighborhood size of its directly adjacent nodes. Conversely to the clustering coefficient, a high revelation coefficient indicates an area of low visual stability, thereby promising an increased information gain during locomotion. Revelation might be especially relevant when actively navigating. In order to facilitate a distinction between enclosure-related measurands and spaciousness, all these measurands were made scale invariant. However, probably due to the scale dependency of architectural features, the findings of Stamps (2005) still suggest correlations with spaciousness.

The third group of factors summarized in the concept of complexity was expected to denote either the absolute amount of information or features, or the relative information density. Reasonable approximations for measuring complexity could therefore be the number of vertices or segments making up the current isovist, vertex density, and again clustering coefficient, or the isovist jaggedness. Similar measurands have been successfully used by Berlyne (1972) to describe pure polygons and by Stamps (2000, pages 39–43) for building silhouettes. Although derived from a quite different theoretical background, an overlap with measurands capturing enclosure becomes apparent (cf also Stamps, 2005).

Finally, normative architectural theory (Ching, 1996) has suggested relations between visual *order* and redundancy patterns, such as symmetries or the absolute and relative numbers of unique polygon sections within the isovists. Since none of the existing measurands from the isovist literature is related to such kinds of geometric properties, several mathematical combinations of basic characteristic values were generated. For an empirical validation of their hypothesized relation to visual order, eight participants sorted printed cards showing sixteen isovist polygon contours (cf figure 2) according to the criterion of introspectively assessed regularity. The subsequent analysis shows a large consistency within the rankings. Two main structural factors become apparent: the average ranking can be described almost perfectly (correlation coefficient $r = 0.94$, $p < .001$) by the formula:

$$\text{polygon regularity} = -\frac{n_{\text{unique polygon sections}}}{n_{\text{symmetry axes}} + 1} .$$

Methodologically, an automatic detection of the number of unique sections of the polygon boundary as well as the number of symmetry axes appears to be difficult, partially owing to issues of mathematical accuracy, partially owing to the unclear relevance of imperfections, suggesting the notion of partial symmetries. Therefore, for the exploratory empirical studies presented in the following section the regularity factors were evaluated manually for each scene only at a single reference point. For automatic analyses of larger numbers, variables based on autocorrelation or formalized measures of entropy (Stamps, 2005) might be superior alternatives.

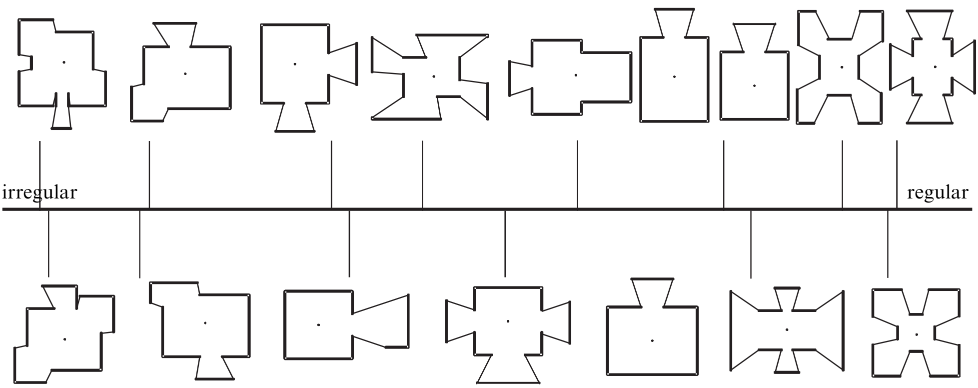
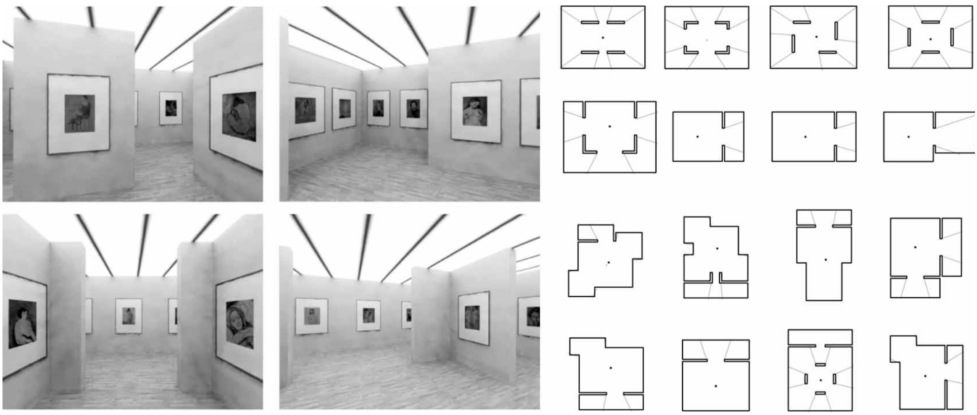


Figure 2. Averaged result of the regularity ranking of isovist polygons by eight participants.

3.3 Empirical results

Two recent experiments (Franz et al, 2005b; Wiener and Franz, 2005) from the domains of architectural psychology and spatial cognition allowed a test of the descriptors presented in the previous section by comparing their theoretic predictions on affective responses with architectural space and on active spatial navigation with human behavior. The experiments made use of sixteen fictive gallery environments (see figure 3) that were presented using a desktop virtual reality (VR) setup and a software system specialized for VR experiments (Franz and Weyel, 2005). VR-based experimental designs were chosen owing to their high level of control and their unique possibility of varying the environments systematically. In the architectural psychology experiment, sixteen participants were asked to rate the experiential qualities of the scenes using a semantic differential comprising six primary dimensions of architectural experience (cf table 2). In the navigation experiment subjects were asked to actively navigate to the positions that maximized the visible area (isovist area) as well as to the position that minimized the visible area.



(a) (b)

Figure 3. (a) Example screenshots of the virtual gallery rooms. (b) The isovists of the central observation points overlayed on the floor plans.

Table 2. English translations and original terms of the rating categories used in the semantic differential. The experiments were conducted in German language.

Category	English low extreme	English high extreme	German low extreme	German high extreme
Interestingness	Boring	Interesting	Langweilig	Interessant
Pleasure	Unpleasant	Pleasant	Unangenehm	Angenehm
Beauty	Ugly	Beautiful	Hässlich	Schön
Spaciousness	Narrow	Spacious	Eng	Weit
Complexity	Simple	Complex	Einfach	Komplex
Clarity	Unclear	Clear	Unübersichtlich	Übersichtlich

The analysis of the rating experiment tested for correlations between the averaged introspective ratings and the isovist-based scene descriptors. The descriptor variables were calculated using a custom-made analysis tool (see http://www.kyb.mpg.de/~gf/anavis). Several strong and significant correlations were found: the differences in the ratings between the scenes could best be explained statistically by the factors vertex density and number of symmetry axes for the valence indicator pleasingness (explained proportion of variance in a multivariate linear regression $R^2 = 0.69$), by isovist area, free near space, the number of symmetry axes, and vertices for beauty ($R^2 = 0.78$), and by isovist roundness, openness ratio, vertex number, and density for interestingness ($R^2 = 0.73$), which is seen as an arousal indicator (cf, for example, Russell, 1988). Regarding the rating dimensions that relate directly to basic spatial properties, rated spaciousness was significantly correlated with both isovist area and free near space ($R^2 = 0.78$), and the analysis of rated complexity found as regressors the number and density of isovist vertices, the number of unique polygon sections, roundness, and openness ratio ($R^2 = 0.93$).

The analysis of the navigation experiment primarily evaluated subjects' performance with respect to finding the best overview and hiding place for each indoor scene by comparing the isovist area at the chosen positions with the isovist area at the positions with the actual highest or lowest values. Additionally, characteristic derivatives of the recorded trajectories—such as navigation time, overall turning angle, traveled distance, velocity, mean turning velocity, and number of stops—were calculated. These behavioral measures were then correlated to global isovist descriptions of the corresponding environments, obtained by averaging over all visibility graph positions. Generally, all sixteen subjects showed a very good and similar performance for both navigation tasks, demonstrating that the area of isovists was well perceptible. Additionally, the subjects' performance in finding the positions that maximized and minimized the visible area for the sixteen indoor scenes were strongly correlated with the single isovist measurands *jaggedness*, *clustering coefficient*, *openness*, and *revelation* (explained proportion of variance in an univariate linear regression $r^2 > 0.35$, $p < 0.02$), while performance was not significantly correlated with the measures for *neighborhood size* and the *number of vertices* (see figure 4). Furthermore, strong correlations were found between, for example, the isovist derivative number of vertices and the trajectory derivatives *navigation time* (correlation coefficient $r = 0.65$, $p < 0.01$), *overall turning angle* ($r = 0.63$, $p < 0.01$), *velocity* ($r = 0.63$, $p < 0.01$), and *traveled distance* ($r = 0.67$, $p < 0.01$).

Taken together, the results of these exploratory experiments provide support for the notion that isovist and visibility graph measurands capture behaviorally relevant properties of space, allowing the prediction of affective responses and navigation behavior. While a separation according to the theoretically independent basic qualities could not be observed in these experiments, the general approach of translating qualitative theories into isovist and visibility graph measurands was clearly affirmed.

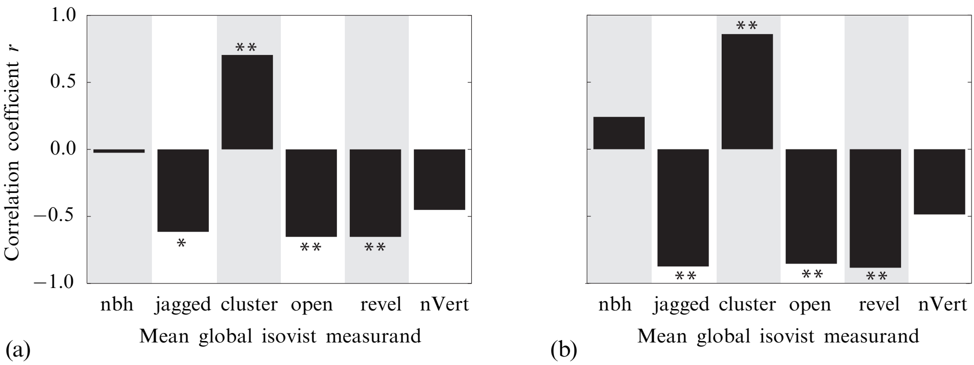


Figure 4. Correlation between subjects' navigation performance and the isovist measurands neighborhood size (nbh), jaggedness (jagged), clustering coefficient (cluster), openness (open), revelation coefficient (revel), and number of polygon vertices (nVert): (a) finding best hiding place; (b) finding best overview place. $*p < 0.05$; $**p < 0.01$.

4 Strategies for selecting local reference points for isovist analysis

The two experiments described above differed with respect to the methods applied to analyze the environments. In the rating experiment the subjects' affective responses were correlated to local isovist and visibility graph measurands that were obtained from a single central position within the environment (see figure 3), whereas in the navigation experiment the subjects' performance was correlated to global measurands obtained by averaging over isovist measurands derived from multiple positions. This methodological difference followed the design of the experiments: as subjects experienced the environments from a static position in the rating experiment, a *local approach* describing spatial properties of the environments from a single corresponding position seemed reasonable. In the navigation experiment, on the other hand, subjects were allowed to freely locomote through an environment. Therefore, a *global approach* describing the environment as a whole was seen as more appropriate. The different analysis methods provoked a more general examination of their potential effects.

Since humans hardly ever experience spatial situations from a single position only, but rather in context of natural movements, a local approach additionally raises the question of how to select the location from which the isovist and visibility graph measures describing the spatial situation are obtained. This issue will be addressed below. Yet simple global strategies also have their limitations and methodological drawbacks. While the virtual indoor scenes depicted in figure 3 were relatively small and completely closed, in real life humans often face environments lacking clear delimitations. In such environments, global approaches that simply average measurands across the whole area will describe the environment at a scale level that is inappropriate for most spatial behavior and will widely ignore the distribution of the underlying data. This will be further discussed in section 5.

4.1 Alternative strategies for selecting local references points

If, for a particular study, measurands capturing local properties of spatial environments are required, one possible approach could be to select their *spatial center* as a reference point. While no indisputable definition can be given for the center of an entire environment a priori, humans mark the center of spatial environments on floor plans remarkably consistently. The results of a respective survey (displayed in figure 5) can be interpreted such that all sixteen participants chose as overall center either a position near to the centroid of the entire environment, the geometrical center of the largest embedded subspace, or they interpolated between these two extremes. In the rating experiment (section 3), the center of the largest subspace was manually preselected. A generalized formalization of this approach is presented in the next section. An alternative straightforward strategy that is generally applicable might be the selection of reference points according to the visibility graph criterion isovist area. The positions that maximize visible area may allow for the best overview and might therefore represent optimally the entire environment. Figure 5 displays the position that maximized the visible area for the virtual indoor scenes used in the case studies as small crosses.

4.2 Statistical comparison

In order to compare these alternative local approaches, for both reference points isovist measurands were calculated in each of the sixteen virtual indoor scenes and were analyzed for correlations. Although the reference points as well as the resulting isovists derived from the two local strategies were obviously different in all environments (cf figure 5), very strong and highly significant intercorrelations between the corresponding isovist measurands were found [$r > 0.70$, $p < 0.01$; cf figure 6(a)]. Additionally, both local approaches were compared with the global values as used in the

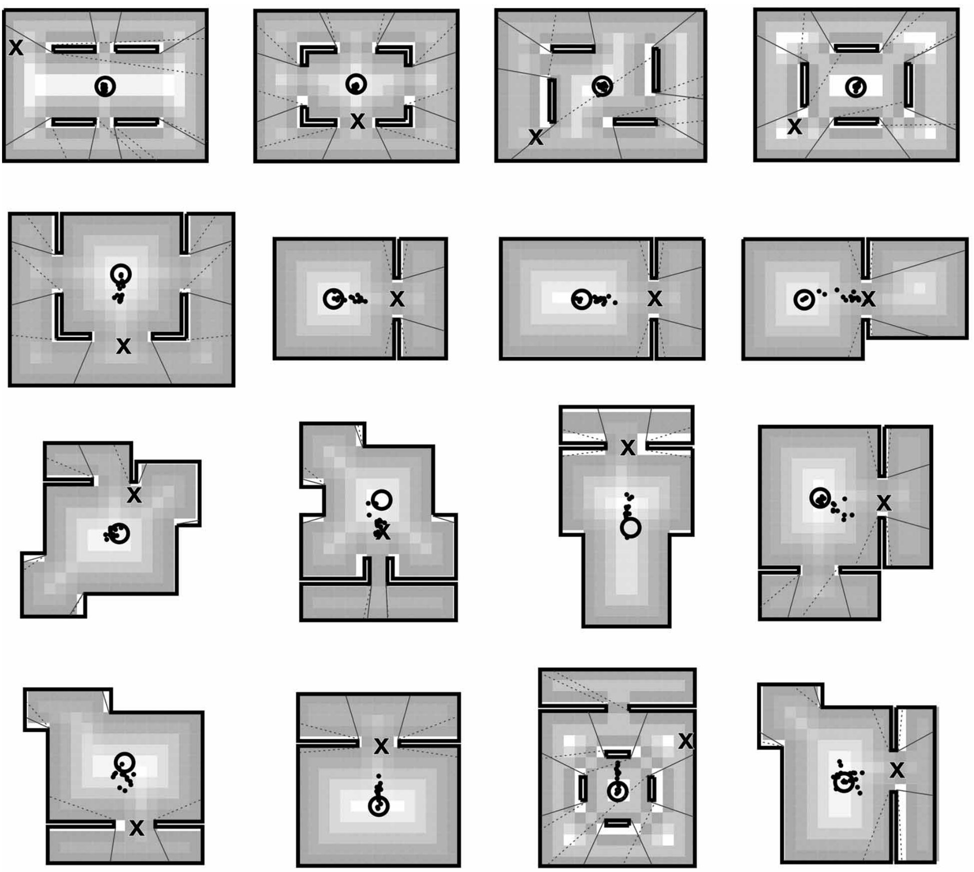


Figure 5. Two different strategies for selecting local reference points for isovist analysis. The central position of the largest subspace is marked by a circle, the position that maximized the visible area is marked by an *X*; responses of sixteen subjects (eight female, eight male) who were asked to mark the central position in each of the environments are shown as dots. The isovists of the two reference points are overlayed on the floor plans (solid lines for the largest subspace, dashed lines for the position that maximized the visible area).

navigation experiment [see figures 6(b) and 6(c)], which were obtained by averaging local measurands calculated at 50 cm distance. Again, the level of intercorrelations between the approaches was surprisingly high ($r > 0.67$, $p < 0.01$).

4.3 Implications

The results of the statistical comparisons indicate that, in the reported behavioral experiments, all three approaches would have explained a similar proportion of overall variance. In other words, the general outcomes appear to be remarkably robust against the selection strategy for the derivation of scene descriptors. Considering the different characteristics of the local reference points and the differently shaped isovists from the respective positions (see figure 5), this result is surprising to say the least. While the spatial center maximized the distances to the spatial boundaries, the positions that maximized the isovist area were often located at transitions between two subspaces, thus offering maximal visual control (or prospect) of the entire environment. A possible explanation for the high level of correlations between the two local strategies might be that not only isovists that maximized the visible area, but also isovists at spatial centers, covered substantial portions of the chosen environments. One might

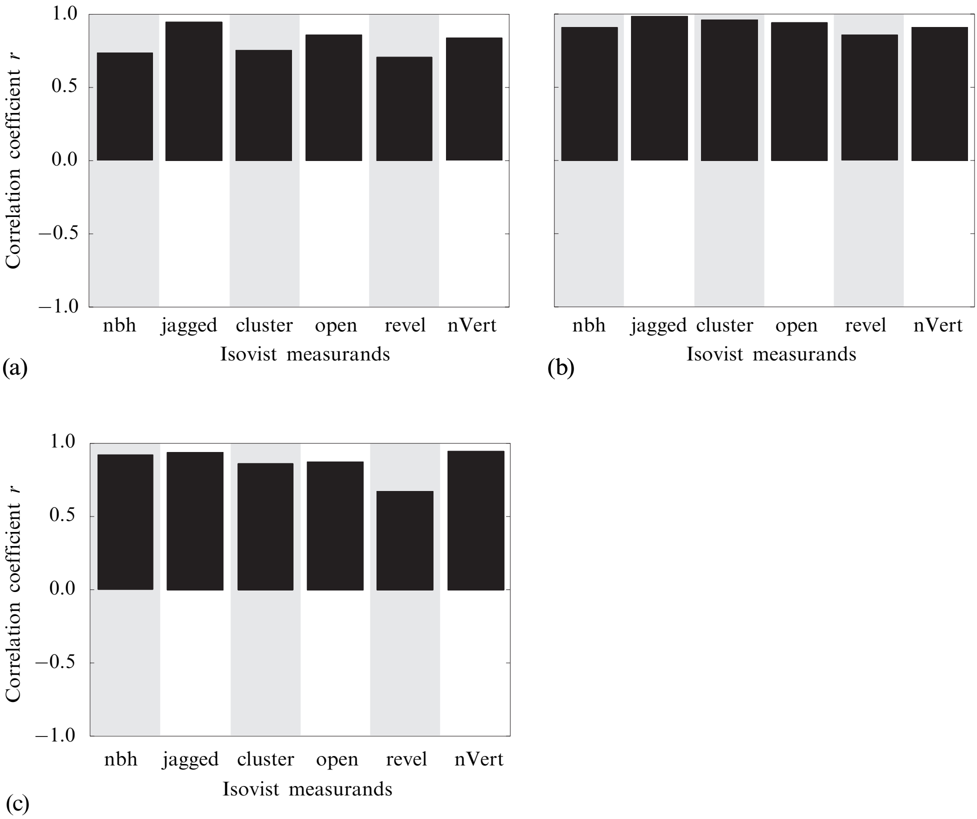


Figure 6. (a) Correlations between isovist measurands obtained from two local reference points: spatial center and maximal isovist area. (b) and (c) Correlations between the local measurands and corresponding averaged global measurands as applied in experiment 2: (b) global average and maximal isovist area; (c) global average and spatial center.

therefore generalize that isovists covering large parts of environments should likely capture essential properties of environments. While an in-depth analysis of the relations between these two types of locations—also referring to their different role and testing the generalizability of the results—is highly desirable, it is beyond the scope of this study.

Taken together, the presented results suggest that, if an experimental question requires a consideration of local spatial properties, measurands obtained from single positions already have significant predictive power. Although the level of correlation and the high degree of communality between judges justifies the manual selection of reference points, formalized generic criteria are nevertheless clearly favorable.

5 A methodology to select multiple reference points in large-scale environmental spaces

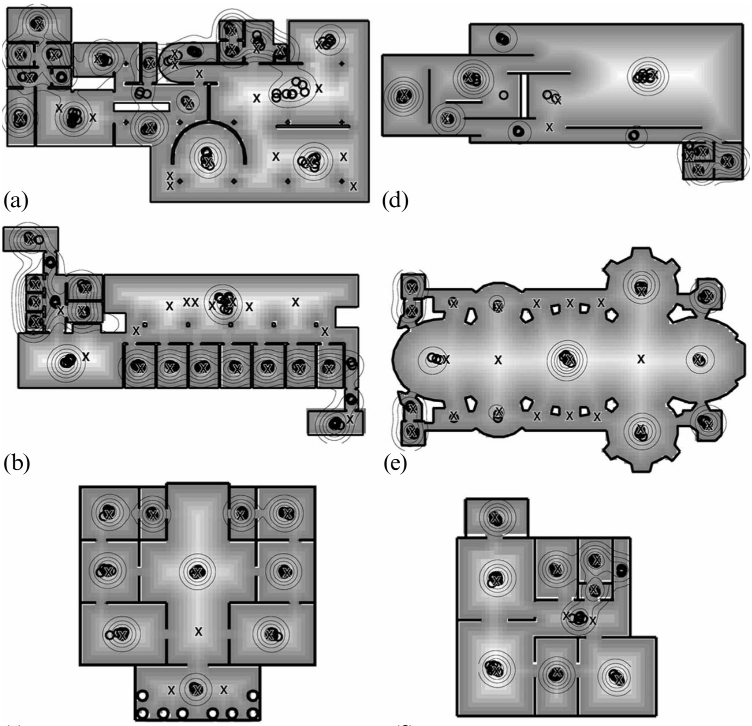
5.1 Introduction

In the previous section three approaches for deriving descriptor variables in small-scale environments were discussed. While, for such vista spaces, all three methods apparently do similarly well, they are self-evidently of limited use for larger environmental spaces. In this case, single reference points are normally poor representatives for the entire environment, and simply averaging disregards local differences. Obviously, a prior subdivision or an individual analysis of multiple reference points is required.

This raises the question of how this can be done in a preferably well-defined and plausible manner. In this section a methodology is presented that formalizes the phenomenal structuring of architectural space in subspaces and individual rooms.

5.2 Background

Architectural environments differ widely with respect to the degree of spatial confinement and definition. In conventional office or residential floor plans individual rooms are normally clearly physically separated and therefore easily identifiable. However, in other environments, such as classical churches or modernistic open-plan buildings, an exact delimitation of individual spatial regions is much more difficult, since here spaces blend rather continuously into each other (cf figure 7). In these cases architectural space might be rather conceived as field having more or less strong inhomogeneities than an array of spatial containers (cf Joedicke, 1985). Rather than basing a definition of subspaces on often hardly definable boundaries, Alexander (2003) has proposed an alternative ontology of architectural space based on the notion of centers. The concept of (relative) centers intuitively fits well both with confined and with open-plan architectural spaces. Also, from a computational point of view, an analysis of few individual positions seems more efficient than a prior subdivision combined with an averaging over many positions. The strategy to reduce the description of complex shapes to the characterization of certain salient positions has already been proposed by Attneave (1954) and studies by de Winter and Wagemans (2004) have provided further empirical evidence. Therefore, the following study explores the degree of communality



(a) (d) (b) (e) (c) (f)

Figure 7. The six floor plans that were used in the desktop experiment on spatial centers in environmental spaces. The individually chosen centers are marked as circles, contour lines illustrate mean trends (Gaussian low-pass filter). The gray shades visualize the distance to the nearest wall. Local maxima, as identified by the algorithm presented in section 5.4, are marked by the letter X.

between humans when identifying local spatial centers in floor plans as well as from an inside perspective. On the basis of this, a simple algorithm is proposed that allows for a formalized and automatic identification of spatial centers.

5.3 Empirical study

In order to get first insights into the degree of communality in the human conception of spatial centers in diverse buildings, in a first condition eight participants were asked to identify individual rooms by marking centers within six floor plans. The sample of buildings contained about ninety rooms and was subjectively selected in order to cover a wide variety of building types and styles. The six floor plans were sequentially presented on a standard desktop computer, subjects marked the centers by performing a drag-and-drop operation using a mouse pointing device. The presentation completely abstracted from any further differentiation—such as materiality, three-dimensional spatial profile, or illumination. Figure 7 synoptically displays the results of the responses of all participants.

As is apparent from the depicted floor plans, the degree of communality between participants was generally very high, especially in buildings mainly consisting of confined spaces [floor plans (b), (c), and (f)]. In the case of open-plan buildings few minor differences, or positions that were marked only by some participants, were recorded [eg the side aisles of building (e) or the largest spaces in plan (d)].

A control experiment explored potential differences between spatial centers experienced from an egocentric inside perspective, in contrast to analyzing a floor plan. For this purpose, eight additional subjects were asked to explore actively the virtual versions of a subsample of three of the previous scenes [floor plans depicted as figures 7(d), 7(e), and 7(f)] and to mark spatial centers analogous to the precedent 2D condition. The experiment made use of a VR laboratory (http://www.cyberneum.de), which allowed for capture of the motions of persons in realtime within an area of 11.7 m $\times$ 15.3 m. The position signal was transmitted wirelessly to a backpack-mounted mobile graphics computer which updated the camera position within the virtual scenes accordingly. As display device, a Trivisio® 3Scope® stereoscopic headmounted display was used, which offers a geometric field of view (FOV) of approximately 32×24 degrees at a resolution of $2 \times 800 \times 600$ pixels. The simulated FOV was twice as large as the physical FOV. While navigating through the environments, subjects marked spatial centers by clicking a joystick button.

As is apparent from figure 8, the spatial centers marked from an inside perspective correspond very well to the results obtained from ground plans. Besides this main trend, the following differences could be tentatively identified: (1) The variance between participants seemed moderately higher in the VR condition. A main cause for this

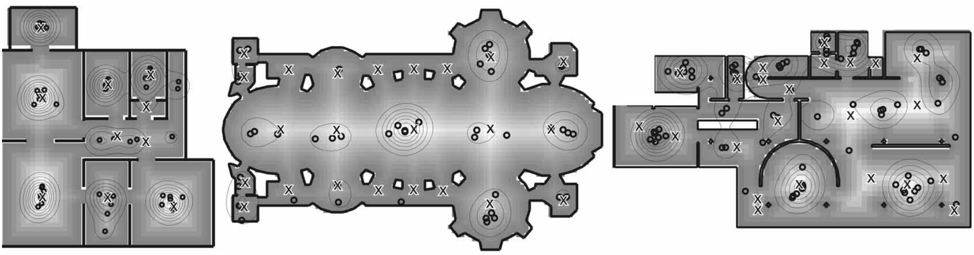


Figure 8. Floor plans of the environments used in the virtual-reality-based control experiment. The individually chosen centers are marked as circles, contour lines illustrate mean trends (Gaussian low-pass filter). Gray shades visualize the distance to the nearest wall as used in the modeling algorithm presented in section 5.4. Local maxima, as identified by the algorithm, are marked by the letter X.

could be the immersive interface which restricts the FOV and introduces viewpoint dependency and influences of exploration. (2) Additionally, positions that offer a good overview (eg in the upper right area of the environment depicted on the right of figure 8) could thereby gain some degree of centrality. (3) There seems to be a stronger influence of scale. Centers of small areas tend to be disregarded more often. Here it has to be considered that, unlike pure floor plans displayed on a screen, the immersive simulation offers plenty of absolute scale information (eg own body, selfmotion, textures) which might increase such tendencies.

5.4 Modeling

Altogether, the empirical experiments presented above suggest a very high level of consensus between humans in identifying spatial centers. In order to formalize the observed behavioral patterns, a three-pass algorithm was designed and implemented:[1]
(1) The architectural environments were initially represented by a visibility graph.
(2) For each graph node the distance to the nearest nonconnected node was calculated, resulting in a discrete matrix encoding the minimum wall distance.
(3) The two-dimensional minimum wall distance matrix was analyzed for local maxima. In the case of neighboring maxima or maxima regions featuring the same minimum wall distance, a single maximum, nearest to their mean position, was selected.

Figures 7 and 8 show a superimposition of the floor plans, the centers identified by human observers, wall distance values encoded in gray shades, and the local maxima represented by X marks, similarly to figure 5.

5.5 Discussion

Methodologically, the discretization of initially continuous space always poses the question of potential side effects of the selected resolution. The selected granularity of 0.5 m resulted from the following considerations: (1) Computational and analytical parsimony suggested taking the lowest resolution possible. (2) The distance of 0.5 m lies between an average human step length (approximately 0.6 m) and an average human body width (approximately 0.45 m) and therefore seemed to be sufficiently fine-grained from a human locomotion behavior-oriented point of view. (3) A significantly coarser resolution for the simplified representation of architectural spaces would be susceptible to missing some features essential for the configuration and navigability of spaces. For example, a sampling of wall openings at a resolution of 1.0 m could miss many typical doors.

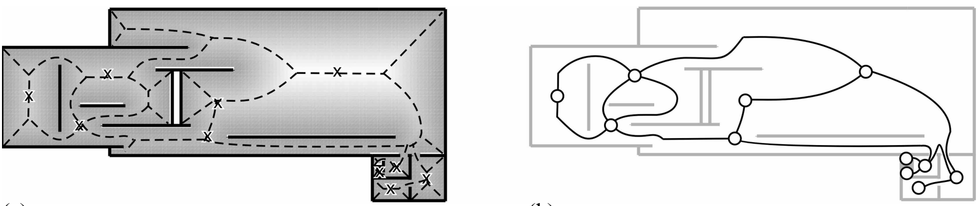
As is apparent from the superimpositions, the algorithm mostly identifies spatial centers very similar to those identified by humans. Although the selected scenes, comprising about ninety spaces, are certainly no representative sample for architectural environments, the obvious success of the algorithm across the diverse examples suggests that the positive result might indeed be generalizable. While initially purely analytically motivated, it is worth mentioning that the basis of the algorithm—that is, local distance to spatial boundaries—also fits well to empirical findings and models of spatial representation in mammal and human brains (Hartley et al, 2000; O'Keefe and Burgess, 1996). Furthermore, maximizing the wall distance means inscribing circles of maximum size within a given spatial environment. In terms of Hillier and Hanson's (1984) theory of the social meaning of spaces, circular subspaces not only provide mutual intervisibility between contained persons, but also form spatial regions

[1] In computational geometry and cognitive robotics a class of similar algorithms are described in the context of the largest empty circle problem or Voronoi graphs—compare, for example, Beeson et al (2005).

featuring an even potential for communication and interaction. Additionally proxemics (Hall, 1966) suggests that humans evaluate other humans, objects, or even open space differently, depending on their egocentric distances. A close wall has a different impact on behavior than a more distant one. Therefore, the detected centers might be interpreted as positions that bring the surrounding walls in an experiential equilibrium. In terms of Lewin's (1982) field theory, these positions of balanced perceptual forces therefore also gain a special valence within an environment.

The few apparent significant deviations may be tentatively ascribed to the following differences between human conception and the algorithm:

- Columns are weighted differently. While the algorithm weights a free-standing column in the same way as a massive wall, humans show a more differentiated behavior. In some cases columns seem to influence the chosen center points in a similar way, as reflected by the algorithm, sometimes they are apparently plainly ignored [in particular, compare figure 7(d)]. These differences in weighting seem to be nontrivial. One might speculate that columns that are positioned exactly in the middle of the surrounding walls are not conceived as being dividing, but rather are seen as a center mark.
- The algorithm detects some centers that lie on very weak local maxima that humans tend to ignore [eg in the side aisles of figure 7(e), or in the largest room of Figure 7(d)]. These cases might be counteracted by introducing an additional minimal contrast threshold between adjacent maxima and in-between minima.
- Humans see additional centers in positions that lie on long constant saddle lines (cf particularly figure 9). These cases might be easily formalized by an additional center rule based on the second derivative.
- The latter two cases might also be partially ascribed to the experimental task that did not allow for differentiations between different degrees of center. In comparison to the centers that are consistently found by participants and the algorithm, the noncorresponding centers appear rather weak. This might also explain the divergence as regards the crossings of example 7(e). Note that the algorithm can also be extended to provide a strength measure—for example, by relating its wall distance to the wall distance of the closest saddle point.



(a) (b)

Figure 9. (a) Sketch of the saddle lines generated by the minimum wall distance algorithm in environment d [see figure 7(d)]. (b) A corresponding place graph based on the maxima and the saddle line skeleton.

Taken together, almost all deviations might be accounted for by minor tweakings. Alternatively, the basic parameter minimum wall distance might also be improved by using related algorithms. For example, instead of counting the radius of the largest empty circle, the largest elliptic bubble having its center at the analyzed position could be used. This variant might be more reliable in finding singular centers within one room and would also introduce some direction specificity analogous to the boundary vectors of place cell models (Hartley et al, 2000). Finally, instead of using variants of local wall distance maxima, the so-called grassfire algorithm (eg Blum, 1973; Duda and Hart, 1973) might be a promising candidate for detecting spatial centers.

5.6 Conclusions

The proposed simple algorithm is capable of identifying spatial centers in floor plans similarly to the way that humans do. Although, in reality, further factors—such as the floor or ceiling profile, or material changes—might influence the experience of centers as well, the positions identified in 2D floor plans appear to be reasonable first approximations of the centers as actually experienced in reality. This opens up the possibility of describing large-scale environments efficiently by concentrating on a small set of well-defined relevant positions. As demonstrated in section 4, the geometric properties of the complete rooms might be well approximated by analyzing the isovists of the spatial centers.

6 Future extensions to automatically derive place graphs

In the field of spatial cognition, place graphs are commonly used as representations of space to study and analyze spatial behavior (see section 2). However, despite this fact, only weakly defined rules exist that describe how these place graphs are generated from the environment. Usually, they are handmade by arbitrarily selecting places (graph nodes) and connections (edges). While this method is applicable for simple environments consisting of clear-cut subspaces or for simple street grids, a more generic and formalized approach would be clearly favorable. In the following discussion an approach that is based on the analysis introduced in the previous section is outlined.

As is apparent from figure 9(a), the spatial positions identified as centers all lie as maxima on saddle lines of maximum wall distance. Interestingly, the saddle and inflection lines of the wall-distance field form a contiguous skeleton of general symmetry axes as described by Leyton (2001) and connect all center points. If this skeleton is reduced to the saddle lines that connect spatial centers, one gets a structure that corresponds to an intuitively correct place graph [cf figure 9(b)]. While the results of this analytical transformation might also decisively depend on the selected resolution, the human scale turned out as a good choice with which to obtain robust results. The minimum wall distance algorithm appears as a useful basis for well-defined place graphs encoding the spatial topology on the basis of the geometry.

In the context of spatial cognition, the forks between nodes in the saddle line skeleton might also be of analytical interest. As is apparent from figure 9, these forks often represent spatial situations at which navigators have to draw decisions about their further path. In navigation experiments such decision points have been shown to have a special meaning. Aginsky et al (1997), for example, found that landmark information was retained only in the vicinity of decision points. The inclusion of the decision points into the place graph might therefore increase the psychological plausibility of the suggested representation of space.

Finally, the wall-distance or degree-of-centeredness field might also be useful for spatial partitioning: each position within an analyzed environment can be either clearly attributed to a single spatial center (by following the vectors perpendicular to the lines of equal wall distance in the positive direction) or lies at the boundary lines between centers and consequently indicates a transition point. Therefore, a catchment area associated with each center might be conceived as corresponding to the extent of a space or room.

7 Conclusions

As is further corroborated by the exploratory studies presented in section 3, human spatial behavior and experience are influenced by the shape and configuration of environments. Research in the fields of architecture and spatial cognition are therefore likely to benefit from description systems capturing behaviorally and psychologically relevant properties of space. In this paper a new integrative framework for the quantitative description of the geometry and topology of architectural environments is introduced that is suitable for research in architectural psychology as well as in spatial cognition.

Isovists and derived measurands are used to describe spatial properties at a local level—that is, spatial properties of single spatial situations. The selected isovist measurands are derived from classic qualitative theories of environmental psychology and their behavioral and psychological relevance have been empirically affirmed. Place graphs are used for the description of the global structure of an environment—that is, of topological relations between different spatial situations. Methods to automatically derive the topological structure of environments have been introduced and tested.

The presented framework lends itself well to deriving behaviorally and psychologically relevant descriptions of spatial properties of environments automatically, both at the local level of single vista spaces and at the global level of environmental spaces. The approach thus allows for quantitative comparisons of the shape and configuration of arbitrarily shaped environments. It therefore appears useful for comparative studies in architectural psychology and spatial cognition.

Furthermore, the described description system constitutes a sparse and efficient representation of spaces and it allows further information to be easily included. For example, metric information at the global level—that is, distances between spatial centers (subspaces), can be added by simply labeling edges. Certainly the presented analyses are rigorous simplifications disregarding likely relevant features such as the three-dimensional shape, surface properties, and the presence of other humans or objects and their functional meaning. Nevertheless, it is our hope that this description system will serve as a first step towards a space semantics—that is, a meaningful representation of space allowing researchers to access its behavioral properties.

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References

Aginsky V, Harris C, Rensink R, Beusmans J, 1997, "Two strategies for learning a route in a driving simulator" *Journal of Environmental Psychology* **17** 317 – 331

Alexander C, 2003 *The Nature of Order: The Phenomenon of Life* (CES, Berkeley, CA)

Appleton J, 1988, "Prospects and refuges revisited", in *Environmental Aesthetics: Theory, Research, and Application* (Cambridge University Press, Cambridge) pp 27 – 44

Arbib M, Lieblich I, 1977, "Motivational learning of spatial behavior", in *Systems Neuroscience* Ed. J Metzler (Academic Press, New York) pp 221 – 239

Attneave F, 1954, "Some informational aspects of visual perception" *Psychological Review* **61** 183 – 193

Batty M, 2001, "Exploring isovist fields: space and shape in architectural and urban morphology" *Environment and Planning B: Planning and Design* **28** 123 – 150

Beeson P, Jong N K, Kuipers B, 2005, "Towards autonomous topological place detection using the Extended Voronoi Graph", in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA-05)* (IEEE Press, Piscataway, NJ) pp 4373 – 4379

Benedikt M L, 1979, "To take hold of space: isovists and isovists fields" *Environment and Planning B* **6** 47 – 65

Berlyne D E, 1972 *Aesthetics and Psychobiology* (Appleton, New York)
Blum H, 1973, "Biological shape and visual science (part I)" *Journal of Theoretical Biology* **38** 205 – 287
Byrne R, 1979, "Memory for urban geography" *Quarterly Journal of Experimental Psychology* **31** 147 – 154
Ching F D K, 1996 *Architecture Form Space and Order* 2nd edition (Van Nostrand Reinhold, New York)
Chown E, Kaplan S, Kortenkamp D, 1995, "Prototypes, location and associative networks (plan): towards a unified theory of cognitive mapping" *Journal of Cognitive Science* **19** 11 – 51
de Winter J, Wagemans J, 2004, "Contour-based object identification and segmentation: stimuli, norms and data, and software tools" *Behavior Research Methods Instruments and Computers* **36** 604 – 624
Duda R, Hart P, 1973 *Pattern Classification and Scene Analysis* (John Wiley, New York)
Franz G, Weyel M, 2005, "veLib reference manual: library version 1.2.0", technical report, Max Planck Institute for Biological Cybernetics, Tübingen
Franz G, Mallot H A, Wiener J M, 2005a, "Graph-based models of space in architecture and cognitive science—a comparative analysis", in *Proceedings of INTERSYMP-2005, 17th International Conference on Systems Research, Informatics and Cybernetics* Ed. G E Lasker (International Institute for Advanced Studies in Systems Research and Cybernetics, Windsor, Canada) pp 30 – 38
Franz G, von der Heyde M, Bülthoff H H, 2005b, "Predicting experiential qualities of architecture by its spatial properties", in *Designing Social Innovation: Planning, Building, Evaluating* Eds B Martens, A G Keul (Hogrefe and Huber, Cambridge, MA) pp 157 – 166
Gibson J J, 1979 *The Ecological Approach to Visual Perception* (Houghton Mifflin, Boston, MA)
Hall E T, 1966 *The Hidden Dimension* (Doubleday, Garden City, NY)
Hartley T, Burgess N, Lever C, Cacucci F, O'Keefe J, 2000, "Modeling place fields in terms of the cortical inputs to the hippocampus" *Hippocampus* **10** 369 – 379
Hillier B, Hanson J, 1984 *The Social Logic of Space* (Cambridge University Press, Cambridge)
Hübner W, Mallot H A, 2002, "Integration of metric place relations in a landmark graph", in *Lecture Notes in Computer Science* number 2415, Ed. J R Dorronsoro (Springer, Berlin) pp 825 – 830
Janzen G, 2000 *Organisation räumlichen Wissens: Untersuchungen zur Orts- und Richtungsrepräsentation* [Investigating the organization of spatial knowledge] (Deutscher Universitäts, Wiesbaden)
Joedicke J, 1985 *Raum und Form in der Architektur: Über den behutsamen Umgang mit der Vergangenheit* [Space and form in architecture] (Kraemer, Stuttgart)
Kaplan S, 1987, "Aesthetics, affect, and cognition: environmental preference from an evolutionary perspective" *Environment and Behaviour* **19** 3 – 32
Kaplan S, 1988, "Perception and landscape: conceptions and misconceptions", in *Environmental Aesthetics: Theory, Research, and Application* (Cambridge University Press, Cambridge) pp 45 – 55
Kuipers B, 1978, "Modeling spatial knowledge" *Cognitive Science* **2** 129 – 153
Leiser D, Zilbershatz A, 1989, "The traveller: a computational model of spatial network learning" *Environment and Behavior* **21** 435 – 463
Lewin K, 1982 *Feldtheorie* [Field theory], volume 4 of *Werkausgabe* (Klett-Cotta, Stuttgart)
Leyton M, 2001 *A Generative Theory of Shape* (Springer, Berlin)
Lynch K, 1960 *The Image of the City* (MIT Press, Boston, MA)
Mallot H A, Gillner S, 2000, "Route navigation without place recognition: what is recognized in recognition-triggered response?" *Perception* **29** 43 – 55
Mehrabian A, Russell J A, 1974 *An Approach to Environmental Psychology* (MIT Press, Cambridge, MA)
Montello D R, 1993, "Scale and multiple psychologies of space", in *Spatial Information Theory: A Theoretical Basis for GIS* (Springer, Berlin) pp 312 – 321
Nasar J L, 1988, "Perception and evaluation of residential street scenes", in *Environmental Aesthetics: Theory, Research, and Application* (Cambridge University Press, Cambridge) pp 275 – 289
O'Keefe J, Burgess N, 1996, "Geometric determinants of the place fields of hippocampal neurons" *Nature* **381** 425 – 428
O'Neill M, 1992, "Effects of familiarity and plan complexity on wayfinding in simulated buildings" *Journal of Environmental Psychology* **12** 319 – 327

Peponis J, Wineman J, Rashid M, Kim S H, Bafna S, 1997, "On the description of shape and spatial configuration inside buildings: convex partitions and their local properties" *Environment and Planning B: Planning and Design* **24** 761 – 781
Robson S K A, 2002, "A review of psychological and cultural effects on seating behavior and their application to foodservice settings" *Journal of Foodservice Business Research* **5**(2) 89 – 108
Russell J A, 1988, "Affective appraisals of environments", in *Environmental Aesthetics: Theory, Research, and Application* (Cambridge University Press, Cambridge) pp 120 – 132
Stamps A E, 2000 *Psychology and the Aesthetics of the Built Environment* (Kluwer, Boston, MA)
Stamps A E, 2005, "Isovists, enclosure, and permeability theory" *Environment and Planning B: Planning and Design* **32** 735 – 762
Turner A, Penn A, 1999, "Making isovists syntactic: isovist integration analysis", paper presented at the 2nd International Symposium on Space Syntax, Brasilia http://www/vr/ucl.ac.uk/publications/isss.pdf
Turner A, Doxa M, O'Sullivan D, Penn A, 2001, "From isovists to visibility graphs: a methodology for the analysis of architectural space" *Environment and Planning B: Planning and Design* **28** 103 – 121
Weber R, 1995 *On the Aesthetics of Architecture: A Psychological Approach to the Structure and the Order of Perceived Architectural Space* (Ashgate, Brookfield, VT)
Wiener J M, Franz G, 2005, "Isovists as a means to predict spatial experience and behavior", in *Lecture Notes in Computer Science* number 3343, Eds C Freksa, M Knauff, B Krieg-Brückner, B Nebel, T Barkowsky (Springer, Berlin) pp 42 – 57
Wiener J M, Schnee A, Mallot H A, 2004, "Use and interaction of navigation strategies in regionalized environments" *Journal of Environmental Psychology* **24** 475 – 493
Zacharias J, 2001, "Path choice and visual stimuli: signs of human activity and architecture" *Journal of Environmental Psychology* **21** 341 – 352