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 need some form of operationalization of space capturing behavioral and psychologically relevant properties and providing a common denominator. This paper presents theoretical and methodological issues arising from the practical application of isovist-based graphs for spatial analysis. Based on recent studies exploring the influence of spatial form and structure on behavior and experience, in particular the following topics are discussed: (1) The derivation and empirical verification of meaningful descriptor variables on basis of classic qualitative theories of environmental psychology relating behavior and experience to spatial properties. (2) Methods to select reference points for spatial analysis at a local level. Furthermore, based on two experiments exploring the human phenomenal conception of the spatial structure of architectural environments, formalized strategies for (3) the selection of reference points at a global or environmental level and for (4) their integration into a sparse yet plausible graph structure describing an environment at a whole are proposed. Taken together, a well formalized and psychologically oriented methodology for the efficient description of spatial properties of environments is outlined. This method appears useful for a wide range of applications from abstract architectural analysis over behavioral experiments to studies on mental representations in cognitive science.

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1 Introduction

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 are probably induced by the shape and configuration of the spatial environment as well as by visuo-spatial characteristics of decision points (cf. e.g., 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, Schnee, & Mallot (2004) have revealed an influence of environmental regions on spatial learning, navigation, and route planning behavior (see also Wiener & Mallot, 2003). Also several theories from environmental psychology such as “prospect and refuge” (Appleton, 1988), “defensible space” (Newman, 1996), or the framework of Balling & Falk (1987) explain human behavior and experience as contingent upon certain features of the environment both within and beyond a given sensory horizon.

While the truth of the initial statement is therefore beyond dispute and corroborated by many studies, it remains difficult to apply individual findings for the prediction of actual behavior in real world environments, mainly because in reality various potentially relevant factors coexist. In order to allow predictions under complex real-world conditions, either a comprehensive overall framework model or at least additional knowledge on the relative weights and on potential interactions between individual factors is required. As an intermediate step towards such more comprehensive approaches, existing theories have to be formulated quantitatively 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 on a wide range of scales from individual rooms to entire city layouts, and at the same time it seems capable and flexible enough to retain a major share of psychologically and behaviorally relevant detail features. Both the isovist and the place graph are established analysis techniques. Mainly in the space syntax community, isovists (Benedikt, 1979) have been used as basic elements for the generic analysis of local geometric properties, whereas in spatial cognition various graph representations are a common tool for the representation of the topology of large-scale
configurations (cf. Franz, Mallot, & Wiener, 2005a). Already (Benedikt, 1979) and later Turner & Penn (1999) have proposed to describe environments by a combination of isovists and graph structures. Both papers suggested graph structures consisting of multiple isovists in non-sparse regular arrays (see also Turner, Doxa, O’Sullivan, & Penn, 2001). In contrast to these rather formally rigid approaches, the topology of graphs in spatial cognition is normally much more irregular and flexible - yet also often ill defined. The methodology outlined in this paper seeks to combine the advantages of both approaches by defining well-formalized rules for flexible graphs that correspond well to the human conception of the spatial structure.

In Section 3 and 4, methodological issues of describing local properties on basis of isovists are discussed. This will be done on basis of recent empirical studies that tested the behavioral relevance of selected isovist measurands. 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 large-scale environments consisting of multiple spaces: (c.) on basis of an empirical study in which humans identified subspaces by marking their centers, a psychologically plausible division of large architectural spaces into subspaces is proposed; (d.) an algorithm that formalizes the behavior recorded before is presented; (e.) a strategy to derive a topological graph on basis of the previously identified elements is introduced.

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

2 Background

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 are viewshed polygons that 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, length of open or closed boundaries (see Figure 1). These basic geometry measurands can be combined to generate further integrated values. For example, the quotient
Graphs in architecture and cognitive science

In architecture, graph-like diagrams are in a long tradition of graphical analysis and have been substantially influenced by the phenomenal city descriptions of Lynch (1960). The need for
strictly formalized description systems arose from the wish to do 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 were seen as close parallels to the underlying social structures (Hillier & Hanson, 1984; Hillier, 1996). Besides applied research, graph investigations in architecture particularly concentrated 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 were explored (Peponis, Wineman, Rashid, Kim, & Bafna, 1997).

In spatial cognition and artificial intelligence, graphs have been used for decades 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 (see also Kuipers, 1978). Ever since, a multitude of such graph-like models of spatial memory have been developed (e.g., Leiser & Zilbershatz, 1989; Chown, Kaplan, & Kortenkamp, 1995). The particular appeal of graph structures as models for spatial memory arises from their superior flexibility as compared to map-like representations of space. For example, while basically being topological structures, by labeling or weighting single edges of graphs, distance and direction information can be included that allow for metric navigation abilities such as short-cutting behavior (Hübner & Mallot, 2002). Additionally, various non-spatial information can be attached to the nodes, for example, places can be labeled with emotional or episodic information (Arbib & 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 (e.g., Mallot & 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, isovists and visibility graphs offer several basic measurands capturing geometrical and local configurational properties of spaces. Already few basic mathematical operations allow the derivation of a multitude of further combined variables, whose meaning
and relevance is difficult to estimate a priori. Actually, due to the vast number of potential combinations, a brute-force analytical approach is practically infeasible, and, moreover, it severely increases the risk of producing significant statistical effects as purely random 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 that offer a qualified basis for empirically testable hypotheses. In the following, existing qualitative theories are analyzed on their underlying spatial properties and tentatively summarized. When appropriate, these assumed basic spatial properties are then related to existing isovist and visibility graph measurands from the space syntax literature (mainly Turner et al., 2001). Likewise, formal measurands described in earlier approaches of empirical aesthetics (e.g., Berlyne, 1972) are transferred on isovists. Furthermore, several additional characteristic values are created by combining basic measurands mathematically in order to capture specific aspects described in theories.

**Theories on spatial qualities**

Already basic adjectives describing spatial size (e.g., narrow, cramped, poky, spacious, ample) have a strong emotional connotation. Analogously, architectural theory (e.g., Joedicke, 1985) suggests that the most basic quality of architectural space, its *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 ecological action theory (Kaminski, 1976, pp. 255-259) makes direct affective responses to spaciousness probable, because the size of a space widely determines the range of possible or preferred utilizations. Additionally, 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 Balling & Falk (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 overlooking other spaces. From the defensible space theory (Newman, 1996) it
can be derived that prospects ideally extend in only one direction, hence, asymmetries in the opening distribution might be important.

Several theories on affective responses to environments relate to perception and information processing. These theories are based on the supposition that environments widely differ in terms of required computational effort in order to interpret them or to encode them into spatial memory. The affective evaluation of these processes is attributed to the stimulus itself, therefore environmental properties that determine the difficulty of these processes also affect the emotional experience (e.g., Berlyne, 1972; Kaplan, 1988; Nasar, 1988; Lozano, 1988; Stamps, 2002). For describing the underlying factors, a bunch of collative concepts and terms such as complexity, diversity, visual entropy, perceptual richness, order, legibility, clarity, and coherence has been used. All in all, there are strong indications for at least two main dimensions within this collection of related concepts, that may be provisionally termed complexity (implicating diversity, entropy, richness) and order (comprising also legibility, clarity, coherence). While architectural theory tends to stress the aesthetic value of the latter (e.g., Weber, 1995), psychological experiments have rather concentrated on effects of complexity. Yet, taken together, the theories suggest that both complexity and order are important basic structural qualities of architecture probably affecting both experience and behavior.

Closely related to these static collative stimulus properties are concepts that relate to the predictability of an environment (e.g., Mehrabian & Russell’s “novelty” and “uncertainty” as part of information rate, 1974, pp. 75-97). Also the “mystery” theory (Kaplan, 1988) suggests behavioral and emotional responses by environments promising new information when moving further. The translation of predictability into formal descriptors seems however difficult, since its effectiveness may strongly depend on non-physical factors such as previous exposure and familiarity. Yet at least aspects of predictability may be related to similar physical properties as the enclosure quality.

**Translation of spatial qualities into isovist measurands**

In the previous section individual theories and findings have been tentatively summarized in four basic spatial qualities spaciousness, enclosure, complexity, and order. Table 1 gives an overview on hypothesized connections to and on the calculation methods of selected isovist measurands.

The basic spaciousness quality was expected to be approximable by measurands such as mere isovist area (also called neighborhood size) or the area of the convex part of the isovist. Since convex partition is mathematically non-trivial and often ambiguous, it was decided to test for
Table 1: Summary of the hypothesized relations between basic spatial qualities and isovist measurands.

<table>
<thead>
<tr>
<th>basic spatial quality</th>
<th>isovist and visibility graph based descriptor variables</th>
<th>calculation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>spaciousness</td>
<td>isovist area free near (medium) space</td>
<td>neighborhood size</td>
</tr>
<tr>
<td></td>
<td>n visible graph vertices at 2 (4) m distance</td>
<td></td>
</tr>
<tr>
<td>openness</td>
<td>isovist openness length open edges / length closed edges</td>
<td></td>
</tr>
<tr>
<td></td>
<td>isovist perimeter² / area</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Σ area adjacent isovists - isovist area) / isovist area</td>
<td></td>
</tr>
<tr>
<td>complexity</td>
<td>number of vertices n isovist vertices, n segments</td>
<td></td>
</tr>
<tr>
<td></td>
<td>vertex density n vertices / area</td>
<td></td>
</tr>
<tr>
<td></td>
<td>roundness isovist area/perimeter²</td>
<td></td>
</tr>
<tr>
<td></td>
<td>jaggedness isovist perimeter² / area</td>
<td></td>
</tr>
<tr>
<td></td>
<td>clustering coefficient n intervisibilities within current neighborhood / (neighborhood size*(neighborhood size -1))</td>
<td></td>
</tr>
<tr>
<td></td>
<td>n segments / n unique segments +1</td>
<td></td>
</tr>
<tr>
<td>order</td>
<td>symmetry n symmetry axes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>redundancy n segments / n unique segments +1</td>
<td></td>
</tr>
</tbody>
</table>

additional influences of distance by partitioning the visibility graph into multiple depth segments and calculating the proportion between actually and theoretically visible graph nodes at the given distances (measurands free near/medium space).

The second quality enclosure was seen to relate to at least two different physical aspects, the availability of vistas into adjacent rooms and the rate of accessibility. The former could probably be captured by measurands describing the convexity of isovists such as clustering coefficient and jaggedness, the latter simply by the physical openness ratio. Furthermore, a more behaviorally oriented measurand was designed called revelation coefficient that was calculated on the visibility graph as the relative difference between the current 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, therefore promising information gain when moving further. 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, pp. 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) suggested to approximate properties contributing to visual order by looking for redundancy patterns within the isovists, such as symmetries or absolute and relative number of unique polygon sections. Since none of the existing measurands from the isovist literature related to such kind 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 16 isovist polygon contours (cf. Figure 2) according to the criterion of regularity. The subsequent analysis showed a large consistency within the rankings. Two structural main factors became apparent: The average ranking could 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 both underlying properties appears to be difficult, partially due to issues of mathematical accuracy, partially due 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. As suggested by Stamps (2005), variables based on autocorrelation or formalized measures of entropy might be superior alternatives for automatically analyzing larger sets of environments.

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

Two recent experiments (Franz, von der Heyde, & Bülthoff, 2005b; Wiener & Franz, 2005) from the domains of architectural psychology and spatial cognition allowed a test of the framework presented in the previous section by comparing its theoretic predictions on affective responses to architectural space and on active spatial navigation to human behavior. The experiments made use of 16 fictive gallery environments (see Figure 3) that were presented using a desktop virtual reality (VR) setup and a software system specialized on VR experiments (Franz & Weyel, 2005). In the architectural psychology experiment, 16 participants were asked to rate the experiential qualities of the scenes using a semantic differential comprising 6 primary dimensions of architectural experience (cf. Table 2) from a fixed central observation point. 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.

The analysis of the rating experiment tested for correlations between the averaged ratings and the isovist-based scene descriptors. The descriptor variables were calculated using a custom made spatial 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 be best explained statistically by the factors vertex density and number of symmetry axes for pleasingness (explained proportion of variance in a multivariate linear regression $R^2=.69$), by isovist area, free near space, the number of symmetry axes and vertices for beauty ($R^2=.78$), and by isovist roundness, openness ratio, vertex number and density for interestingness ($R^2=.73$). Regarding the rating dimensions that directly relate to the basic spatial qualities, rated spaciousness was significantly correlated with both isovist area and free near space ($R^2=.78$), and the analysis of rated complexity found as regressors number
Table 2: English translations and original terms of the rating categories used in the semantic differential. The experiments were conducted in German language.

<table>
<thead>
<tr>
<th>Category</th>
<th>English low extreme</th>
<th>English high extreme</th>
<th>German low extreme</th>
<th>German high extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>interestingness</td>
<td>boring</td>
<td>interesting</td>
<td>langweilig</td>
<td>interessant</td>
</tr>
<tr>
<td>pleasure</td>
<td>unpleasant</td>
<td>pleasant</td>
<td>unangenehm</td>
<td>unangenehm</td>
</tr>
<tr>
<td>beauty</td>
<td>ugly</td>
<td>beautiful</td>
<td>hässlich</td>
<td>schön</td>
</tr>
<tr>
<td>spaciousness</td>
<td>narrow</td>
<td>spacious</td>
<td>eng</td>
<td>weit</td>
</tr>
<tr>
<td>complexity</td>
<td>simple</td>
<td>complex</td>
<td>einfach</td>
<td>komplex</td>
</tr>
<tr>
<td>clarity</td>
<td>unclear</td>
<td>clear</td>
<td>unübersichtlich</td>
<td>übersichtlich</td>
</tr>
</tbody>
</table>

and density of isovist vertices, number of unique polygon sections, roundness and openness ratio \(R^2=.93\).

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 actually 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 was calculated. All these behavioral measures were then correlated to global isovist descriptions of the corresponding environments, obtained by averaging over all visibility graph positions. Generally, the 16 subjects showed a very good and similar performance for both navigation tasks, demonstrating that the area of isovists was well perceptible. Additionally, subjects’ performance in finding the positions that maximized and minimized the visible area for the 16 indoor scenes strongly correlated with the single isovist measurands jaggedness, clustering coefficient, openness, and revelation (explained proportion of variance in an univariate linear regression \(r^2>.35, p<.02\)), 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 \(r=.65, p<.01\)), overall turning angle \(r=.63, p<.01\), velocity \(r=.63, p<.01\), and traveled distance \(r=.67, p<.01\).

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 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).

4 Strategies for selecting local reference points for isovist analysis

The two experiments described above differed with regard to the applied spatial analysis. In the rating experiment 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 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 for a more general examination of their potential effects.

In contrast to the rating experiment described in Section 3, humans almost never 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 is obtained. This issue will be addressed below. Yet also simple global strategies 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. This issue will be further discussed in Section 5. Another issue concerning global strategies is the question of how to summarize the global isovist measures. By
simply averaging over the local isovist measurands one widely ignores the distribution of the underlying data. All positions within the environment are treated as being equally important, which is most probably not a valid assumption.

**Alternative strategies for selecting local reference 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 reference point. While no unique definition can be given for the center of an entire environment a priori, humans mark the center of spatial environments on floor plans remarkably consistent. The results of a respective survey (displayed in Figure 5) can be interpreted such that all 16 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 selected. A generalized formalization of this approach is presented in the next section. An alternative straightforward strategy that is generically 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 the entire environment best. Figure 5 displays the position that maximized the visible area for the virtual indoor scenes used in the case studies as small crosses.

**Statistical comparison.** In order to compare these alternative local approaches, for both reference points isovist measurands were calculated in each of the 16 virtual indoor scenes.
Figure 6: Left: Correlations between isovist measurands obtained from two local reference points. Middle and right: Correlations between the local measurands and corresponding averaged global measurands as applied in Experiment 2.

and 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 significant intercorrelations between the corresponding isovist measurands were found ($r > .70$, $p < .01$, cf. Figure 6 left). Additionally, both local approaches were compared to the global approach as used in the navigation experiment (see Figure 6 middle and right). Here the global isovist measurands were obtained by averaging local measurands calculated on a 50 cm grid covering the entire environment. Again, the level of intercorrelations between the approaches was surprisingly high ($r > .67$, $p < .01$).

Implications. The results of the statistical comparisons implicate that in the reported behavioral experiments all three approaches would have explained a similar proportion of overall variance. In other words, the general outcomes appeared to be remarkably robust against the selection strategy for the derivation of scene descriptors. Hence, if an experimental question requires a consideration of local spatial properties, the results suggest that already measurands obtained from single positions have significant predictive power. While the level of correlations and the high degree of communality between judges justifies the manual selection of reference points, formalized generic criteria are nevertheless clearly desirable.

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

Introduction. In the previous section, three approaches were discussed how to derive descriptor variables in small-scale environments spanning single simple or articulated spaces, either by averaging over the whole environment, by taking the position featuring the largest isovist, or by manually selecting the center of the largest subspace. While for small-scale vista spaces all three methods apparently do similarly well, it is self-evident that they are of limited use for the analysis of larger environmental spaces. In this case, single reference points are normally poor representatives for the entire environment, and simply averaging dis-
regards 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.

Background. Architectural environments widely differ with respect to the ease of subdiv-
diding them into subspaces. In conventional floorplans as the majority of office or residential
environments individual rooms are normally clearly physically separated and therefore easily
identifiable. Whereas in others, such as classical churches or modernistic open-plan build-
ings, an exact delimitation of individual spatial regions is much more difficult, since here
spaces rather continuously blend into each other (cf. Figure 7). Therefore, architectural space
in its entirety 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 physical limits, Alexander (2003) has proposed an alter-
native ontology of architectural space that is initially based on the notion of centers than on
boundaries. The concept of (relative) centers intuitively fits well both to confined and open-
plan architectural spaces. Also from a computational point of view, an analysis of spatial
properties that is based on few individual positions seems more efficient than a prior subdi-
vision in combination with an averaging over many positions. Therefore, in the following a
study is presented that explored the degree of communality between humans when identifying
local spatial centers in floorplans as well as from an inside perspective. Based on this,
a simple algorithm is proposed that allows for a formalized and automatic identification of
spatial centers.

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 their centers within six floorplans. The sample
of buildings contained about 90 rooms and was subjectively selected in order to cover a wide
variety of building types, styles, and both open-plan and conventional spatial concepts. The
six floorplans were sequentially presented on a standard desktop computer, subjects marked
the centers by performing a drag-and-drop operation using a mouse pointing device. Figure
7 synoptically displays the results of the responses of all participants.

As apparent from the depicted floorplans, the degree of communality between participants
was very high. In buildings mainly consisting of confined spaces (floor plans b, c, and f), all
participants identified very similar positions as spatial centers. Also in open-plan buildings,
the level of consensus was fairly high as regards most centers, solely in few cases (e.g., the
side aisles of building e or the largest spaces in plan d) few minor differences or positions
Figure 7: The six floor plans that were used in the desktop experiment on spatial centers in environmental spaces. Eight participants were asked to identify spatial centers on the floor plans (circles). The contour lines illustrate the probable mean trends in the empirical data as revealed by a low-pass Gaussian filtering. The gray shades visualize the distance to the nearest wall, which was the basis of the modeling algorithm presented in the following section. Increasing wall distances are visualized by lighter shades of gray, local maxima as identified by the algorithm are marked by the letter X.
Figure 8: Floor plans of the environments used in the virtual reality based control experiment. Eight participants were asked to identify spatial centers on the floor plans (circles). The contour lines illustrate the probable mean trends in the empirical data as revealed by a low-pass Gaussian filtering, assuming a standard deviation of 0.5m. Additionally, the gray shades visualize the distance to the nearest wall, which was the basis of the modeling algorithm presented in the following section. Increasing wall distances are visualized by lighter shades of gray, local maxima as identified by the algorithm are marked by the letter X.

that were marked only by a fraction of the participants were recorded.

A control experiment explored potential differences between spatial centers experienced from an egocentric inside perspective in contrast to analyzing a floorplan. For this purpose, eight additional subjects were asked to actively explore the virtual versions of a subsample of three of the previous scenes (floorplans depicted as subfigures 7 d, e, f) and to mark spatial centers analogous to the precedent 2D condition. The experiment made use of a virtual reality (VR) laboratory (www.cyberneum.de) which allowed for capturing the motions of persons in realtime within an area of 11.7m x 15.3m. 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 light-weight Trivisio® 3Scope® stereoscopic head-mounted display was used which offers a geometric field of view (FOV) of approximately 32x24 degrees at a resolution of 2x800x600 pixels. The simulated FOV was twice as large as the physical. While navigating through the environments, subjects marked spatial centers by clicking a joystick button which resulted in placing a virtual cone at their current location.

As apparent from Figure 8, the spatial centers marked from a realistic inside perspective correspond very well to the results obtained from ground plans. Besides this apparently dominant main trend, the following differences could be tentatively identified: (1) The variance between participants seemed moderately higher in the VR condition. A main reason for this could be the immersive interface which restricts the field of view and introduces viewpoint dependency and influences of exploration. (2) Additionally, positions that offer a good overview (e.g., in the upper right area of the environment depicted on the right of Figure 8) could thereby gain some degree of centrality. (3) Finally, 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 of-
fers plenty of absolute scale information (e.g., own body, selfmotion, textures) which makes it very likely to amplify such tendencies. Furthermore, the virtual environments had to be down-scaled in order to fit into the laboratory.

**Modeling.** Altogether, the empirical experiments presented above suggested a very high level of consensus between humans in identifying spatial centers, the qualitative results corresponded well to the outcomes of the study in Section 4. Therefore, in order to formalize the observations, the authors designed and implemented a three pass algorithm\(^1\) that seemed capable of identifying similar centers:

1. Analogous to a visibility graph, the architectural environments were initially represented by an occupancy grid-like regular graph, the graph nodes encoded accessibility, edges encoded intervisibility between nodes.

2. In a first analytical step, for each graph node the distance to the nearest non-accessible or not connected node was calculated, resulting in a discrete matrix encoding the minimum wall distance for each accessible position.

3. In order to approximate the spatial centers marked by the participants in the empirical study, the graph was analyzed for local maxima in the two dimensional minimum wall distance matrix. In 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 floorplans, the centers identified by human observers, the minimum wall distance values encoded in gray shades, and the local maxima represented by x marks. Likewise, Figure 5 displays the minimum wall distance values computed by the algorithm as gray shades.

**Discussion.** As apparent from the superimpositions displayed in Figures 5 and 7, the described algorithm mostly identifies the same or very similar spatial centers as humans do. Although the selected scenes comprising about 90 spaces certainly cannot claim to be a representative sample for architectural environments, the preponderant success of the algorithm across the diverse examples suggests that the positive general result might be indeed generalizable. While initially purely analytically motivated, it is worth mentioning that the basis of the algorithm, i.e. local distance to spatial boundaries, also fits well to empirical findings and models of spatial representation in mammal and human brains (O’Keefe & Burgess, 1996; Hartley, Burgess, Lever, Cacucci, & O’Keefe, 2000). The few apparent significant deviations may be tentatively ascribed to the following differences between human conception and the algorithm:

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1 In computational geometry and cognitive robotics, a class of similar algorithms are described in context of the largest empty circle problem or Voronoi graphs, cf. e.g., Beeson, Jong, & Kuipers (2005).
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, in other cases they are apparently plainly ignored (in particular cf. Figure 7 d). These differences in weighting seem to be a non-trivial special case. One might speculate that columns that are positioned exactly in the middle of the surrounding walls are not conceived as dividing, but are rather seen as a center mark.

The algorithm detects some centers that lie on very weak local maxima that humans tend to ignore (e.g., 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 that is required between adjacent maxima and the intermediate minima.

Humans see additional centers in positions that lie on long constant saddle lines, although they eventually lead to real maxima (cf. particularly Figure 9). These cases might be easily formalized by an additional center rule based on the second derivative, the exact threshold needs to be determined by further empirical tests.

The latter two cases might be also partially ascribed to the experimental task that did not allow for differentiations between different degrees of centers. In comparison to the centers that are consistently found by participants and the algorithm, the non-corresponding centers appear rather weak. This might also explain the divergence as regards the crossings of the naves of example 7 e. Note that the algorithm can also be extended to provide a strength measure, e.g., by relating it’s wall distance to the wall distance of the closest saddle point.

Taken together, almost all deviations between the center positions marked by humans and the algorithm could be accounted for by some minor tweaking or by introducing additional rules complementing the maxima detection. Alternatively, also the basic parameter minimum wall distance might be improved by using related algorithms. For example, instead of counting the radius of the largest empty circle, the largest elliptic bubble having the center at the analyzed position could be used. The algorithm would be identical except that the minimum wall distance circle is expanded along the axis perpendicular to the nearest wall until the resulting ellipsis is tangent to a further wall. 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 (e.g., Blum, 1973; Duda & Hart, 1973) might be a promising candidate for detecting
spatial centers. It repeatedly thins regions or spaces from their edges until collapsing in a single point, which can be conceived as the spatial center. A comprehensive comparative analysis of such algorithms preferably in comparison to centers rated by humans in 3D space appears as a viable approach to decide between them.

**Distinctive characteristics of centers.** In the previous paragraph it was argued that computational approaches similar to the chosen wall distance maxima algorithm offer a promising basis for detecting and describing spaces based on their centers. Based on the geometric properties underlying the algorithm, some characteristics of the identified positions shall be discussed.

Already Attneave (1954) has proposed that extrema provide the most information about shapes. His empirical investigations have shown that humans perceive extrema as the most salient points, de Winter & Wagemans (2004) have demonstrated that extrema play an important role in the identification and classification of shapes. While these studies relate to contours, the results of the experiments presented above suggest that the general concept might be transferable on extrema in space. It is obvious that from an inside perspective particularly the maxima play an important or literally central role.

Furthermore, maximizing the wall distance means inscribing circles of maximum size within a given spatial environment. Indeed, the locally largest circular areas as detected by the algorithm are often good approximations to largest concave subspaces. In contrast to a (much more complex and potentially indeterminate) algorithm that identifies maximally large concave subspaces, the chosen algorithm prefers subspaces featuring low distances between its contained spatial positions, in other words, the catchment areas have rather homogeneous properties. In terms of Hillier and Hanson’s (1984) theory of social meaning of spaces, circular or almost circular subspaces do not only provide mutual intervisibility between contained persons, but also offer comparatively similar potentials for communication and interaction.

Also from a functional point of view not only the area but also the shape of spaces influences the utility potential of a space: for many actions rather the minimum than the maximum diameter available is the decisive criterion whether a space is useful or not.

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, 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. Analogously, Alexander, Ishikawa, & Silverstein (1977, pp. 883-887) have suggested that humans have innate preferences for spaces that
surround them at approximately equal distances.

Furthermore, the described algorithm is often capable of identifying positions featuring maximum local symmetries. This at first glance stunning coincidence can be explained by the fact that centers often lie on crossings of saddle and inflection lines of the minimum wall distance field and by looking at their further geometrical properties. As apparent from Figure 9 left, these saddle and inflection lines correspond to general symmetry axes as described by Leyton (2001). So in sum, spatial centers appear as prominent positions within spaces, as places of special meaning. Research interested in behavioral or affective responses to places should be aware of these exceptional characteristics.

Conclusions. The proposed simple algorithm is capable of identifying spatial centers in floorplans similarly as 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 floorplans appear as a reasonable first approximations of the centers as actually experienced in reality. This opens up the possibility to describe 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 A methodology 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 hand-made by selecting all possible places (graph-nodes) as well as all the connections between these places (edges). While this method is applicable for simple environments consisting of clear-cut subspaces or for simple street grids, a more generic approach would be clearly favorable. In the following, a method that is based on the analysis introduced
in the last section is discussed allowing for the automatic derivation of place graphs.

As apparent from Figure 9 left, the spatial positions identified as centers all lie on saddle lines of maximum wall distance. In conjunction, these saddle lines form a contiguous skeleton of symmetry axes connecting all center points. If this skeleton is reduced to the saddle lines that actually connect spatial centers, one gets a structure that corresponds to an intuitively correct place graph encoding spatial centers as place nodes. Skeleton lines correspond to bidirectional graph edges (cf. Figure 9 right). Therefore, the minimum wall distance algorithm allows for well-defined place graphs encoding the spatial topology on basis of the geometry.

In the context of spatial cognition, also the forks between nodes in the saddle line skeleton might be of analytical interest. As 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, Harris, Rensink, & Beusmans (1997), for example, monitored subjects’ spatial knowledge of a virtual environment during the learning of a route. They found that landmark information was retained only in the vicinity of decision points (for similar results see also Allen, Kirasic, Siegel, & Herman, 1970; Cohen & Schlopfer, 1980). 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. While the proposed center-oriented analysis has the advantage of not premising such a partitioning, it might itself be a promising and well defined basis for that: Each position within an analyzed environment can be either clearly ascribed to a single spatial center (by following the vectors perpendicular to the lines of equal wall distance in positive direction) or lies exactly at the saddle lines between centers and therefore indicates a transition point between centers. Therefore, a catchment area associated with each center might be conceived as corresponding to the extent of a space or room.

7 Conclusions

As further corroborated by the exploratory studies presented in Section 3, human spatial behavior and experience depends on the shape and configuration of environments. Any research in the fields of architecture and spatial cognition therefore requires 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 environments was introduced that is suitable for research in architectural psychology as well as
in spatial cognition. The basic elements of the proposed framework are isovists and place graphs.

Isovists and derived measurands are used to describe spatial properties at a local level, i.e. spatial properties of single spatial situations. The selected isovist measurands were derived from classic qualitative theories of environmental psychology and their behavioral and psychological relevance was empirically affirmed. Different approaches for the automatic selection of the local reference points for the isovist analysis in complex environments consisting of multiple subspaces were introduced and empirically verified.

Place graphs are used for the description of the global structure of an environment, i.e. of topological relations between different spatial situations. Methods to automatically derive the topological structure of environments were introduced and tested.

In principle, the presented framework allows behaviorally and psychologically relevant descriptions of spatial properties of environments to be automatically derived, both at the local level of single vista spaces and at the global level of environmental spaces. The described description system 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 allowing for further insights into the mechanisms and strategies underlying spatial behavior and experience.

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, i.e. distances between spatial centers (sub-spaces), can be added by simply labeling edges. It is the authors’ hope that this description system will serve as a first step towards a space semantics, i.e. a truly semantic representation of space allowing researchers to access its behaviorally meaningful properties. Further research will investigate whether such a space semantics requires further spatial and non-spatial features relevant for behavior, such as the 3-dimensional shape, surface properties, or objects and their functional meaning.

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