

## **ON THE EVALUATION OF ARCHITECTURAL FIGURAL GOODNESS:**

*a foundation for computational architectural aesthetics*

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### **Abstract**

The first stage of an investigation into the quantification and computability of architectural aesthetics is reported. Issues considered include the function, sources and role of aesthetic analysis in architecture in the framework of a *descriptive* approach to architectural analysis and design. The main focus is on the applicability of the concept of figural goodness to architectural aesthetics and the derivation of a representation for architectural form suitable to this purpose.

### **1. Aesthetics, analysis and evaluation**

The paper discusses certain issues in the representation of architectural forms which relate to the perceptual coding of images and visual figural goodness. These issues are seen as the foundation of most cognitive processes in architecture, including recognition and memorization. In the present paper they are considered with respect to one specific application, the quantification of aesthetic analysis and evaluation. The importance of aesthetics in architecture and the sensibilities connected to it require a clear statement of the underlying approach and in particular of the hypotheses concerning:

- the function of aesthetic preference in architectural design, as well as in lay interaction with the built environment and its representations;
- the sources of aesthetic preference, i.e. the innate structures and the cognitive reference frames involved in aesthetic analysis and evaluation;
- the role of aesthetics relative to other design aspects in architecture;

- the computability of aesthetic analysis and evaluation.

The intuitive appreciation of aesthetic preference has been one of the hallmarks of architectural design in practice. It has also been one of the main reasons for conflict between the architect and the lay person, as the latter's appreciation of built form and space is less tempered by dominant architectural doctrines and more by the élite that dictates good taste and vogue. As vogue is often at odds with architectural history and criticism, architects have been reluctant to change what they consider to be part of their methodical background. The predominance of the intuitive approach agrees with many types of human interaction with the built environment and its representations. This agreement adds an element of common sense to architectural analysis that may temper indifference to practical problems. However, common sense can be distorted or even refuted by expert opinion and interpretation, especially if the specific human experiences do not involve directly measurable performance criteria. Such distortions and refutations have contributed to the deep dichotomy between form and function in architecture and to the frequent elevation of formal considerations to the highest priority in architectural design, either as a priori norms and canons or as direct and inescapable consequences of functional issues and problems.

Within reasonably well-defined architectural systems formal considerations are in the final analysis part of the constraints of the problem, and specifically of the professional knowledge that constitutes the framework of many design decisions. This has frequently allowed concentration on particular problems and resolution of these problems in ways that satisfied not only the intrinsic formal constraints but also extrinsic performance criteria. In an eclectic period like ours formal considerations lose much of their coherence and consequently much of their value as guiding principles. At the same time their arbitrariness is accentuated by their frequent use as justifications for design decisions that may be otherwise unrelated to the problem. The abuses of aesthetic analysis urge a rigorous, in-depth treatment of aesthetic questions which reveals the true extent and significance of architectural aesthetics and its relations to other design aspects. The basic premises of this treatment are:

- Aesthetics is one of many design aspects that have to be considered in an architectural problem. It is essentially similar and equivalent to functional aspects such as circulation and environmental aspects such as daylighting.
- Aesthetic evaluation is a performance measure and as such it should reflect the interaction between human activities and the built environment that contains these activities. Corollaries of this include:
  - The psychology of perception and cognition are the basic sources of aesthetic analysis and evaluation. This has been common ground in architectural treatises of aesthetics where cognitive psychology has been the main source of explanations for intuitive or conventional aesthetic devices and preferences (Prak 1968; Arnheim 1974; Arnheim 1977; Prak 1979; Arnheim 1988; Holgate 1992; Weber 1995).

- Aesthetic evaluation should be based on explicit qualitative or quantitative cognitive criteria which replace the often ill-defined architectural norms. In this much can be learned from attempts to quantify aesthetics in general and more specifically in relation to information processing (Birkhoff 1933; Bense 1954; Moles 1968). The prototypical character of these attempts necessitates knowledge transfer from recent research into the quantification of figural goodness, also largely on the basis of information processing. This transfer is the main subject of the present paper.

Equally important to the sources and the relative significance of aesthetic analysis and evaluation is how it should be performed: by which means and towards which goals. Architectural analysis and design (including aesthetic issues) have been driven by normative models belonging to either of the following deontic approaches:

- *Proscriptive*: formal or functional rules that determine the acceptability of a design on the basis of non-violation of certain constraints. Formal architectural systems such as classicism and modernism, as well as most building regulations are proscriptive systems.
- *Prescriptive*: systems that suggest that a predefined sequence of actions has to be followed in order to achieve acceptable results. Most computational design approaches are prescriptive in nature.

As stated earlier, dominance of a specific system or approach in general has been instrumental for the evolution of architecture, as it allowed for concentration of effort on concrete, usually partial problems within the framework of the system and hence supported innovation and the transformation of innovation into global improvement. The strongly eclectic spirit of recent and current architecture reduces greatly the value of normative approaches, as it permits strange conjunctions, arbitrary deviations, far-fetched associations and unconstrained transition from one system to another. In addition, the advent of the electronic era provides through the democratization of computer technologies the means for analyses and evaluations of a detailed and objective nature. These dispense with the necessity of abstracting and summarizing in rules and norms. By this I do not suggest that abstraction is unwanted or unwarranted. On the contrary, abstraction is an obvious cognitive necessity that emerges as soon as a system has reached a stable state, is widely applicable and free from major internal conflicts which may reduce reliability. As a result, one can expect the emergence of new abstractions on the basis of the new detailed, accurate and precise analyses. It is probable that several older norms will be among the new abstractions. This, however, does not imply that we should adopt the top-down strategy followed in many computational studies, i.e. accept unquestioningly current norms and then elaborate these norms in rule-based systems and naïve ‘simulations’. Abstraction should occur in a bottom-up fashion that supports new strategies which match the complexity and priorities of today’s design problems.

The main characteristic of the new forms of analysis is that they follow an approach we may term *descriptive*. They evaluate a design indirectly by generating a description of a particular aspect comprising detailed measurable information on the projected

behaviour and performance of the design. This description is normally closely correlated with the formal representation of the design and therefore permits interactive manipulation, e.g. for trying different alternatives and variations. In short, the descriptive approach complements (rather than guides) human design creativity by means of feedback from which the designer can extract and fine-tune constraints.

In functional analyses it has become clear that most current norms and their underlying principles have a very limited scope, namely control of minimal specifications by a lay authority. They are often obsolete as true performance measures and grossly insufficient as design guidance. The solution presented by the descriptive approach is the substitution of obsolete abstractions with detailed information on functionality and performance, for example abandonment of Blondel's formula of stair sizes in favour of an ergonomic analysis of stair ascent and descent by means of simulation (Mitossi and Koutamanis 1996). The analysis is performed in a multilevel system that connects normative levels to computational projections and to realistic simulations in a coherent structure where the assumptions of one level are the subject of investigation at another level (Koutamanis 1995; Koutamanis 1996).

The approach advocated in the present paper is accordingly an extension of the principles underlying descriptive functional analyses. It is proposed that we should continue to draw the principles of architectural aesthetics from perceptual and cognitive sources and connect these principles to architectural issues but strictly in this order. In other words, rather than starting with ordering the existing architectural aesthetic norms and then proceeding to a search for cognitive relevance and justification, we should attempt to apply general computational models of perception and cognition to architecture. One reason for doing so is the difficulty involved in attempting to form a cohesive system out of disparate cognitive explanations of architectural aesthetic preferences. Another reason is the lack of a suitable theory of architectural perception and visual cognition, i.e. one that links architectural theory with cognitive science and especially with the latter's spectacular advances in the last quarter of our century. Such a theory should not derive from a normative architectural model or system, i.e. should not exhibit any bias towards or against specific approaches. The aesthetic analysis of an architectural object or configuration should potentially accommodate all possible architectural systems (Stiny and Gips 1978). Different systems would correspond to variations in the analysis with respect to the configuration of analytical devices, as well as to (parametric) differences within each device. The common basis of the different systems and of the corresponding analyses is an objective representation of the architectural object, i.e. a description that does not relate to a specific architectural formal system.

The prerequisite of an objective representation brings us to a third reason for commencing our investigation of architectural aesthetics from cognitive science. This reason, which arguably underlies the previous two, is the lack of general agreement concerning the architectural representation of built form and space. Our approach is based on the assumption that the basic components of this representation are the conventional 'solids' and 'voids' of architecture (i.e. building elements and the spaces bounded by the building elements) and their relationships. Lower level

(implementation) primitives such as points and lines, as well as Platonic and other abstract prototypical forms, are deemed irrelevant. The main departure from existing related representations, notably the dual graph representation (Steadman 1976; Steadman 1983), lies in that identification and representation of individual components relies less on architectural knowledge and convention and more on visual cognition. Architectural knowledge is treated as a cognitive reference frame against which the perceptual system constructs descriptions of the objects (Rock 1973; Palmer 1989; Rock 1990).

The distinction between the derivation of a description, its interpretation and finally its evaluation is common to computational studies of vision but also of aesthetics (Stiny and Gips 1978). In our case its particular value lies in that it stresses the importance of the representation for aesthetic analysis and thereby of the affinity between figural goodness in perception and the aesthetic appreciation of built form. Figural goodness has been linked to aesthetic response by means of the relation between perceptual arousal and complexity (Berlyne 1960; Berlyne 1971). The working hypothesis of our research is that the representation of architectural objects is subject to coding on the basis of figural goodness. The coding relates to preference for a specific configuration in the percept and hence for a particular interpretation of the object. Architectural aesthetic analysis and evaluation is based on placing this interpretation and coding against a background of cognitive reference frames derived from architectural formal systems. The present paper is a discussion of three basis corollaries of this hypothesis:

- the decomposition of aesthetic analyses into quantifiable factors relating to architectural figural goodness;
- the coding of a representation in relation to figural goodness; and
- the derivation of an architectural representation which supports evaluation and analysis of figural goodness.

## **2. Aesthetic measures**

The first significant attempt to quantify aesthetics was by the American mathematician George D. Birkhoff who effectively established a prototype for subsequent approaches (Birkhoff 1933). In Birkhoff's analysis the aesthetic experience relies on principles of harmony, symmetry and proportion previously stated by among others the Pythagoreans and Leibniz and suggests three successive phases:

1. arousal and effort of attention;
2. the feeling of value or aesthetic measure which rewards the effort of attention; and finally
3. the realization that the perceived object is characterized by a certain aesthetic order.

Birkhoff states that the effort of attention is proportional to the complexity ( $C$ ) of the perceived object and links complexity, the aesthetic measure ( $M$ ) and aesthetic order ( $O$ ) in the basic aesthetic formula:

$$M = O / C$$

Complexity is generally measured by the number of elements in the perceived object. For example, in isolated polygonal forms complexity is measured by the number of distinct straight lines containing at least one side of the polygon, similarly to the gratings of rectangular dissections (Steadman 1983). The measurement of order varies with the specific class of objects to be evaluated but generally takes the form of the sum of weighted contributing elements:

$$O = ul + vm + wn + \dots$$

where  $l, m, n, \dots$  are the independent elements of order and  $u, v, w, \dots$  indices which may be positive, zero or negative, depending upon the effect of the corresponding element. Aesthetic order and consequently the aesthetic measure are relative values which apply to specific classes of objects so restricted that intuitive comparisons of the different objects becomes possible. There is no comparison between objects of different types.

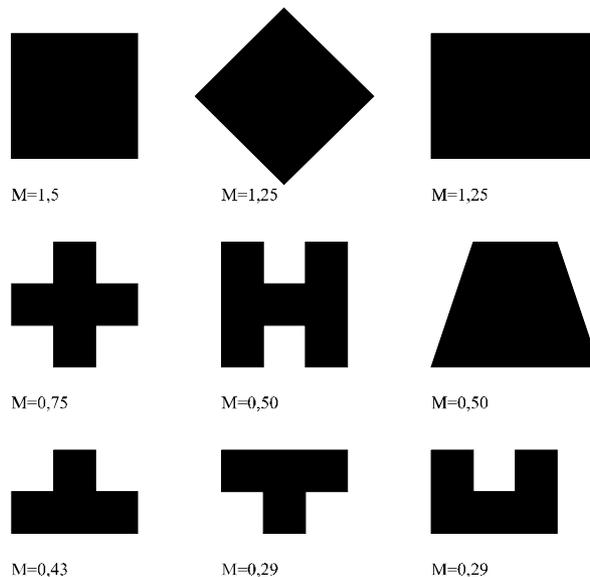


Figure 1. The aesthetic measure of isolated polygonal forms according to (Birkhoff 1933)

Birkhoff suggests that order relates to associations with prior experience and acquired knowledge that are triggered by formal elements of order, that is properties of the perceived object, such as bilateral symmetry about a vertical axis or plane. Formal elements of order which have a positive effect include repetition, similarity, contrast,

equality, symmetry and balance. Ambiguity, undue repetition and unnecessary imperfection have a negative effect. For example, a rectangle almost but not quite a square is unpleasantly ambiguous according to Birkhoff. Also a square whose sides are aligned with the horizontal and vertical is superior to an unnecessarily imperfect square which has been rotated about its centre by 45 degrees “because it would be *so easy* to alter it [the rotated square] for the better” (p. 25).

In the example of isolated polygonal forms aesthetic order is measured by the formula

$$O = V + E + R + HV - F$$

where *V* stands for vertical symmetry, *E* for equilibrium, *R* for rotational symmetry, *HV* for the relation to a horizontal-vertical network (reference framework) and *F* for unsatisfactory form. “Unsatisfactory form” encompasses too small distances between vertices or parallel sides, angles too near to 0 or 180 degrees and other ambiguities, diversity of directions and lack of symmetry.

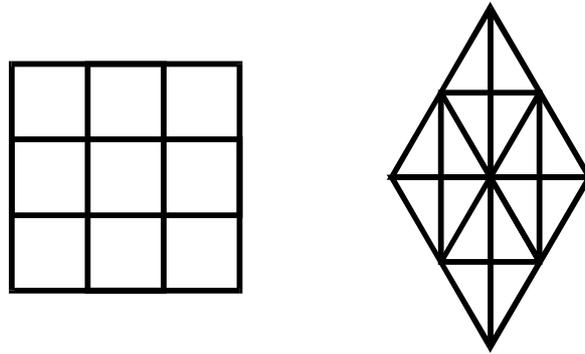


Figure 2. Examples of horizontal-vertical networks according to (Birkhoff 1933)

Ingrained aesthetic prejudices reduce the applicability and reliability of Birkhoff's aesthetic measure. The highest values are achieved with symmetrical forms with the least number of parts. The square with sides aligned to the vertical and horizontal is the clear winner among polygonal forms, followed by the square rotated by 45 degrees and the rectangle with horizontal and vertical sides. Still, the aesthetic measure is important to our investigation for three basic reasons relating more the way the measure is calculated and less to the measure itself. The first is that it equates beauty with order. While this does not hold for aesthetics in general, it is obviously relevant to prescriptive and proscriptive architectural formal systems where conformity to canons and rules, which are often explicitly and paradigmatically expressed, constitutes the usual measure of formal acceptability. The second reason is the factoring of aesthetic order into discrete, independent formal elements with a limited scope each. This too is related to the (didactic) analyses of architectural formal systems. For example, the elements of symmetry and the horizontal-vertical framework in the order measure of polygonal forms has obvious correspondences with the symmetry and taxis levels of classical architecture (Tzonis and Lefaivre 1986). The third reason is the roles of order and

complexity in the aesthetic measure and their affinity with information processing and the role of figural goodness in perception. This affinity was not lost on Birkhoff's epigoni who have linked aesthetic measures to information theory (Bense 1954; Moles 1968).

The applicability of Birkhoff's approach to architectural aesthetics is consequently restricted to (a) the analysis of factors contributing to aesthetic appreciation and preference and (b) the evaluation of an object with respect to each of these factors. The benefits of such analyses and partial evaluations lie mainly in the deeper understanding of the nature and relative significance of each factor, especially when the evaluations are founded on perceptual and cognitive models. One example of the correlation between analyses of architectural objects and of perception is the following evaluation of symmetry in classical floor plans.

Tzonis and Lefaivre have described the classical canon as a system of elements, relationships and coordinating devices which constrain rather than direct design decisions (Tzonis and Lefaivre 1986). This system consists of three major levels: *genera*, *taxis* and *symmetry*. The term *genera* (preferred over 'orders') denotes the "well-determined sets" of architectural elements which are formed on the basis of fixed local relations. *Taxis* is responsible for the overall organization of a classical building and contains two sublevels (schemata): the *grid*, which parametrically divides the building into spatial components, and tripartition. A rectangular grid and a simple tripartition schema produce a 3 x 3 pattern. The deletion, addition, repetition and embedding of parts in this generic pattern transforms it into the layout of a classical building, including Wittkower's 5 x 3 Palladian grid (Wittkower 1952). *Symmetry* is the collection of relationships that constrain the positioning of a particular genus inside the divisions determined through *taxis* with respect to each other and to the overall structure of *taxis*.

A similar approach to symmetry is encountered in the work of Stephen Palmer who has considered basic organisational phenomena in perception, such as figural goodness, perceptual grouping and reference frame effects, with respect to local invariance over the group of Euclidean similarity transformations (Palmer 1983; Palmer 1985). He claims that the perceptual system analyses the incoming stimulus information with respect to five fundamentally different but interrelated properties, shape, position, orientation, size and sense. Four of these five basic perceptual properties are intimately linked to simple transformation groups:

- translations along a line (position);
- rotations about a point (orientation);
- dilations (radial expansion and contraction) about a point (size); and
- reflections about a line (sense).

Earlier researchers have linked transformational invariance and figural goodness in evaluations of invariance following eight transformations: central rotations through angles of 0, 90, 180 and 270 degrees and reflections about vertical, horizontal, left

diagonal and right diagonal lines through the centre (Garner and Clement 1963; Garner 1974). Palmer extends the notion of invariance under rotation and reflection to other possible transformations, notably dilations and translations, and to reference frame effects (differences in goodness due to different types of symmetries) by treating the transformations as a mathematical group (a set of elements plus a composition operation for putting them together such as that a few properties hold). For each figure there is a set of transformations that leave the figure completely invariant. This set is a subgroup of the initial group of possible transformations and is called the *symmetry subgroup*, as it relates to the mathematical notion of symmetry (Weyl 1952).

The level of symmetry in the classical canon bears close resemblance to the notion of symmetry in the invariance model of figural goodness. The correspondences have been investigated in classical floor plans at three different levels:

- internal symmetry of each space;
- symmetry within each group of spaces; and
- global symmetry of groups in the overall floor plan.

In all cases the taxis schema which determines the global tripartition of the floor plan has been taken as the reference frame for the transformations (Koutamanis 1990). The choice of a reference frame relates to what Palmer terms *the reference frame hypothesis*, i.e. that the effects of the transformations are neutralized by an intrinsic frame of reference which ensures constancy of shape and configuration (as opposed to the invariant features hypothesis which states that shape is represented by detecting those properties of objects that do not change over the relevant set of transformations) (Palmer 1983).



Figure 3. Invariance of a classical floor plan under transformation (Koutamanis 1990)

The results of the analysis provide a quantitative measure of symmetry for both individual spaces and groups of spaces. Even more significant is that symmetry forms a strong preference criterion for choosing between alternative descriptions of whole floor plans, i.e. different configurations of space groups. Especially in compact floor plans where grouping relationships can be interpreted in different ways symmetry can be the primary criterion for preferring or even accepting a description, as taxis and its containment of space groups is generally unambiguous (Koutamanis 1990).

### 3. Coding and information

Probably the greatest shortcoming of Birkhoff's approach lies in that it fails to take account of perception, that is, of the processes by which an object elicits a pleasurable reaction. By linking aesthetics to perception we depart from the objectiveness of Birkhoff's measure and adopt an inter-subjective model of aesthetic appreciation which stresses the cognitive similarities that exist between different persons and cultures (Scha and Bod 1993). Inter-subjectivity also allows us to correlate different aesthetic approaches, in our case different architectural formal systems. This is largely due to the reason for such cognitive similarities, the organization of perceptual information.

Gestalt psychologists have formulated a number of principles (or 'laws'), such as proximity, equality, closure and continuation, which underlie the derivation of a description from a percept by determining the grouping of its parts (Köhler 1929; Koffka 1935; Wertheimer 1938). Probably the most important and certainly the most mysterious of the Gestalt principles of perceptual organization is *Prägnanz* or *figural goodness* which refers to subjective feelings of simplicity, regularity, stability, balance, order, harmony and homogeneity that arise when a figure is perceived. Figural goodness ultimately determines the best possible organization of image parts under the prevailing conditions. As a result, it is normally equated to preference for the simplest structure. The principle is seen as the basis for preferring one out of several possible alternative descriptions of a percept.

The view of perception as information processing has led to attempts to formulate figural goodness more precisely. Given the capacity limitations of the perceptual system and the consequent necessity of minimization, it has been assumed that the less information a figure contains (i.e. the more redundant it is), the more efficiently it could be processed by the perceptual system and stored in memory (Attneave 1954; Hochberg and McAlister 1954). Palmer's model of invariance under transformation, which has been discussed previously in this paper, is similarly motivated.

Arguably the best model in this line of investigation has been Leeuwenberg's coding or *structural information theory* (Leeuwenberg 1967; Leeuwenberg 1971). According to Leeuwenberg a pattern is described in terms of an alphabet of atomic primitive types, such as straight line segments and angles at which the segments meet. This description (the *primitive code*) carries an amount of structural information ( $I$ ) that is equal to the number of elements (i.e., instances of the primitives) it contains. The structural

information of the primitive code is subsequently minimized by repeatedly and progressively transforming the primitive code on the basis of a limited number of coding operations:

- iteration, by which the patterns

$$a a a a a b b b b b b \quad (I = 12)$$

$$a b a b a b a b a b a b \quad (I = 12)$$

become respectively

$$6 * [(a) (b)] \quad (I = 3)$$

$$6 * [(a b)] \quad (I = 3)$$

- reversal, denoted by  $r[\dots]$ :

$$a b c = r [c b a] \quad (I = 3)$$

Reversal allows the description of symmetrical patterns ( $\Sigma$ ):

$$a b c c b a = a b c r [a b c] = \Sigma [a b c] \quad (I = 4)$$

$$a b c b a = a b c r [a b] = \Sigma [a b (c)] \quad (I = 4)$$

- distribution:

$$a b a c = \langle (a) \rangle \langle (b) (c) \rangle \quad (I = 3)$$

- continuation ( $\subset \dots \supset$ ), which halts if another element or an already encoded element is encountered:

$$a a a a a a \dots a = \subset a \supset \quad (I = 1)$$

The coding process returns the *end code*, a code whose structural information cannot be further reduced. The structural information ( $I$ ) of a pattern is that of its end code.

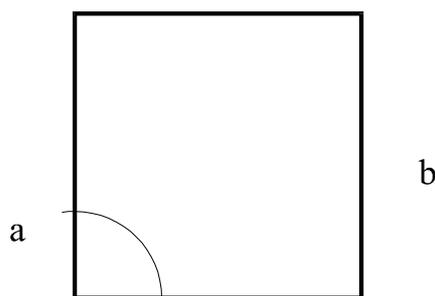


Figure 4. Coding of square:  $a b a b a b a b = \subset a b \supset \quad (I = 2)$

The structural information of a pattern is a powerful measure of its figural goodness. By equating a figure's goodness with the parametric complexity of the code required to

generate it we can both derive the different descriptions an image affords and choose the one(s) that contain the least information. Especially in situations where two or more descriptions are equally acceptable to the human perceiver, as in the Necker cube illusion, measurement of structural information clearly demonstrates that the preferred descriptions are normally equally compact. This suggests that structural information theory is particularly suited to untangling complex, overlapping or intertwined patterns, i.e. situations which are amenable to evaluations of figural goodness by e.g. invariance under geometric transformations only following an initial analysis which segments and disambiguates the image.

With respect to architectural aesthetics we should note the similarities between the measurement of figural goodness on the basis of structural information (including the way an image is coded) and aesthetic analyses by means of shape grammars (Gips 1975; Stiny 1975; Stiny and Gips 1978). For example, the evaluation of floor plans generated by the Palladian grammar (Stiny and Gips 1978) is based on:

- local criteria derived from the floor plans of Andrea Palladio's actual villas; and
- a global aesthetic measure.

The local measures are essentially similar to the generative shape rules of the Palladian grammar and concern either individual spaces or groups of cells in the underlying 3 x 3, 5 x 3 or 5 x 4 grid. The global aesthetic measure is defined as the ratio of the length of the description of a plan (i.e. the sum of the number of cells required for the multicell space types in the plan and of the number of instances of each of these types in the plan) to the length of the information required for its generation (i.e. the number of shape rules required for the generation of the plan).

The local criteria form expressions of Palladian constraints and as such are quite effective in the determining the acceptability of an artificial floor plan on the basis of its similarity to actual designs by Palladio. The global measure, on the other hand, is a measure of the "specificational simplicity" of a plan and therefore a test of the operations and control structures that comprise the Palladian grammar. In other words, the global measure is the equivalent of figural goodness within the framework of a particular shape grammar, even through the relationships between the components of a shape grammar, design decisions and perception can be at times tentative.

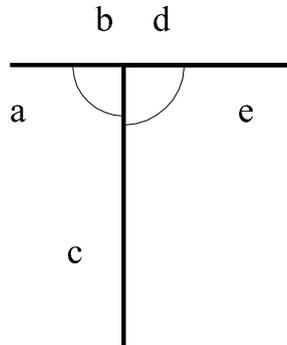


Figure 4. Coding of branching with bifurcation signs:  $a \{b c\} d e$   
 (meaning: after  $c$  return to end of  $a$  and proceed to following  $d$ )

Of particular interest to our investigation is the ability of coding to recognize and evaluate alternative groupings of image parts on the basis of basic, purely formal quantitative relationships. These relationships and the resulting group forms are implied in Gestalt theory, as well as in computational architectural representations such as shape grammar and rectangular arrangements. The explicitness of groups in structural information theory and the causal relationship between the configuration of groups and figural goodness satisfy fully one of the basic requirements of our investigation, the correlation of a structured representation with aesthetic evaluation and preference.

#### 4. Architectural primitives

The main problem of theories of perceptual organization, from Gestalt to structural information theory, lies in that they are developed and discussed within abstract domains of simple, mostly two dimensional patterns and elementary primitives such as dots and line segments. Such basic geometric forms should be treated with caution in evaluations of design aspects, as they occupy the lowly level of implementation mechanisms in representations (Marr 1982). The confusion between implementation mechanisms and symbols has been a major obstacle in the evolution of computational design. Moreover, given the highly conventional character of existing architectural representations it is doubtful that the use of implementation mechanisms such as line segments as the basic primitives for architectural aesthetic analyses would reveal much beyond the conventions themselves.

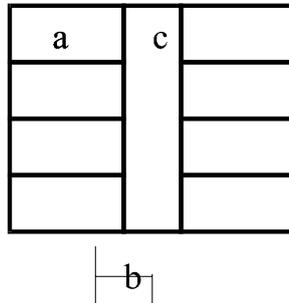


Figure 5. Coding of a floor plan:  $a a a a b c b a a a a =$   
 $4 * [(a)] b c b 4 * [(a)] = \Sigma [ 4 * [(a)] b (c) ] \quad (I = 5)$   
 The end code is a symmetric tripartite configuration of  
 two space groups flanking a central space.

An extension to the three dimensional forms of the built environment and to the complex two dimensional representations employed in architecture involves the main problem of determining the primitives of these domains. It also invariably increases the complexity of descriptions, as these primitives relate to each other in multiple ways. An initial investigation of the applicability of structural information theory to floor plans has been based on the choice of spaces as the primitives and of formal grouping derived from the chain code as the relationships between primitives (Koutamanis 1990). Even though this investigation has been restricted to establishing preference for one of several previously recognized alternative descriptions of a floor plan in terms of space groups, it made evident that coding efficiency and economy are closely related to intuitive interpretations of architectural figural goodness, also with respect to formal aesthetic devices such as classical symmetry and tripartition.

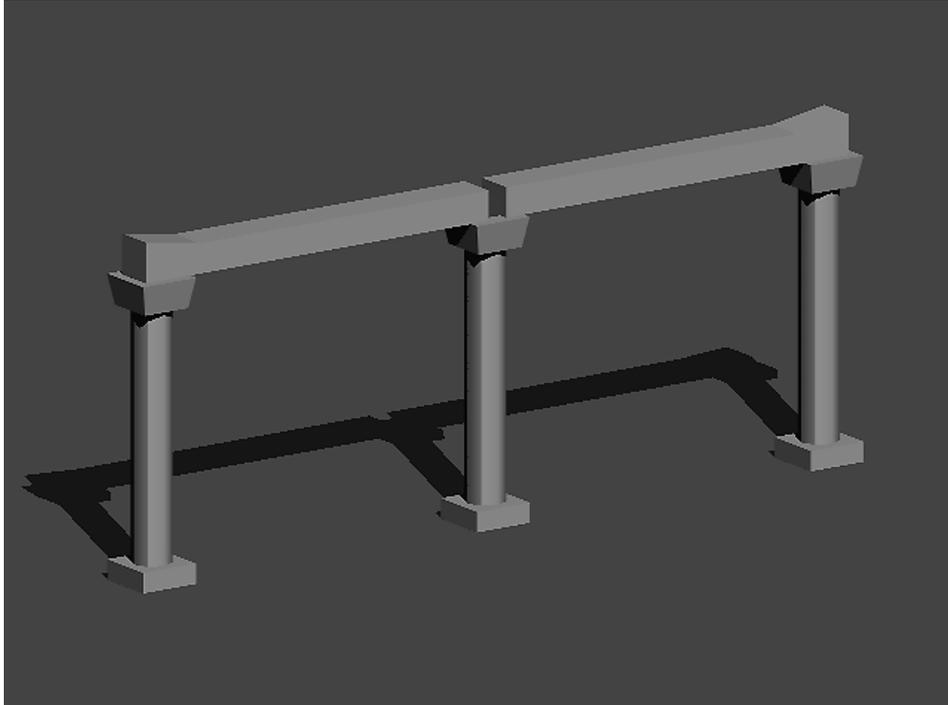


Figure 6. An architectural scene

Many of the problems we encounter in attempts to discover or define the primitives of architectural design are due to a confusion between the real built environment, its architectural representations and the conventions underlying these representations. For this reason we have adopted a sharp distinction between the analysis and manipulation of representations and the perception of and interaction with the built environment. The former rely firmly on architectural conventions and should be accordingly considered from the viewpoint of architectural knowledge. The adoption of building elements and spaces as the primitives of such representations offers pragmatic advantages which should not be neglected. The ability to integrate directly explicit architectural knowledge and the possibility of equally direct correspondences between specifications, regulations or other requirements and the representation of a design form the basis of most design analyses and a responsive background to taking design decisions.

On the other hand, the extension of conventional architectural representations to the perception of built form and space adds little beyond a specialized memory element to general human interaction with the built environment. A preferable starting point is general computational models of perception and recognition which could be enriched with the specialized modes of architecture. These provide a better understanding of perceptual and cognitive devices that also underlie architectural design and analysis. In addition to their direct applicability to the analysis and recognition of realistic

architectural scenes they could also ultimately lead to improvements in existing architectural representations.

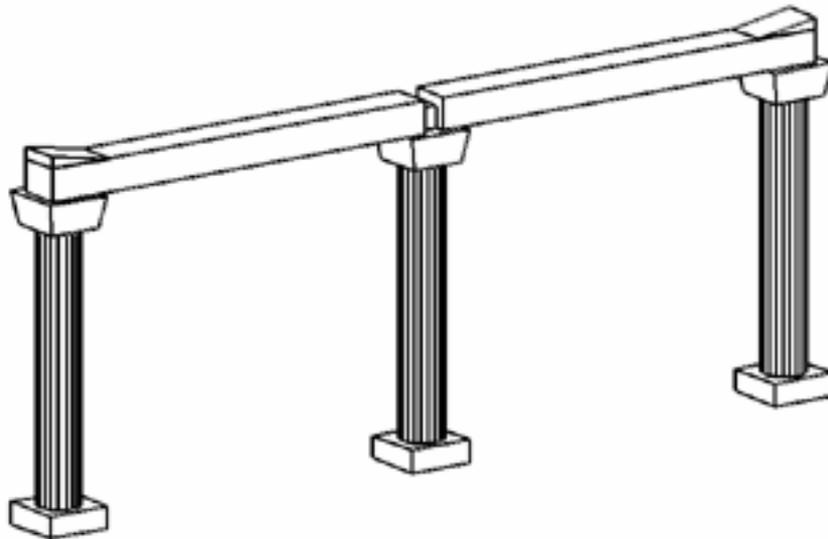


Figure 7. A decomposition of figure 6 into geons

Once low level processing is completed, the first stage in the recognition of a scene is invariably a decomposition of its elements into simple parts, such as the head, the body, the legs and the tail of an animal. The manner of the decomposition into parts does not depend on completeness and familiarity. An unfamiliar, a partly obscured animal or even a nonsensical shape are decomposed in a more or less the same way by all observers (Biederman 1987). The detection of where parts begin and end is based on the *transversality principle* which states that whenever two shapes are combined their join is almost always marked by matched concavities (Hoffman and Richards 1985). Consequently segmentation of a form into parts usually occurs at regions of matched concavities, i.e. discontinuities at minima of negative curvature. The results of the segmentation are normally convex or singly concave forms.

At first sight one might expect that there is an unlimited number of part types. However, with his *recognition-by-components* theory Biederman has proposed that these forms constitute a small basic repertory of general applicability, characterized by invariance to viewpoint and high resistance to noise. He calls the forms *geons* and suggests that they are only 24 in number (Biederman 1987; Biederman 1995). Geons can be represented by generalized cones, i.e. volumes swept out by a variable cross section moving along an axis (Binford 1971; Brooks 1981). A scene is described by structured explicit representations comprising geons, their attributes and relations derived from only five edge properties.

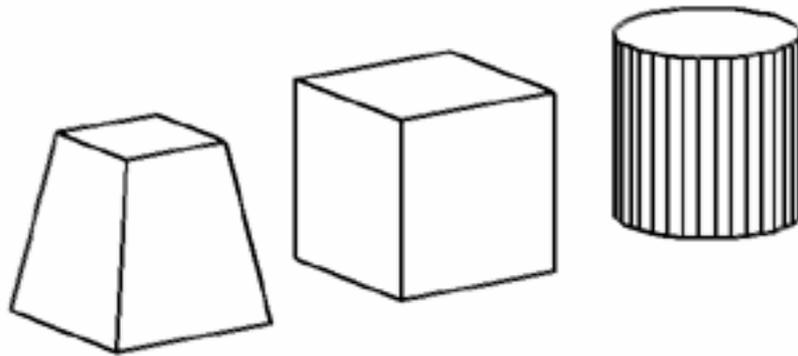


Figure 8. The geons in figure 7

The recognition-by-components theory appears to be as applicable to architectural scenes as to any other scene or object. Decomposition into geons is essentially similar to conventional decomposition into solid building elements and components. The main difference lies in the sensitivity of recognition-by-components to changes in the geometry within what is architecturally a single element. In most cases, however, an element that is decomposed into two or more geons is either a composite element, such as a wall with half columns or pilasters, or a geometrically complex object, such as a T- or L-shaped wall.

A combination of structural information theory and recognition-by-components resolves the problems of both theories with respect to our evaluation of figural goodness. The addition of a compact set of real-world primitives liberates structural information theory from the abstraction of elementary line drawings and extends its applicability to realistic scenes. In Biederman's model coding according to the structural information theory means that there can be grouping of a higher order than local binary relationships. This allows for the development of multilevel representations (hierarchical modular structures (Marr 1982)) which are less complex, better structured and ultimately more meaningful than atomistic relational representations (Koutamanis 1996; Koutamanis 1997). Moreover, the combination of the two theories makes it possible to establish general preference criteria for alternative descriptions on the basis of code compactness which in turn relies on formal grouping principles.

The application of this combination to architectural scenes concentrates in first instance on the definition of primitives and relationships. In that respect, the only deviation from the original theories concerns the relationship that is ignored in coding. In structural information theory this is horizontal alignment. In our investigation we have opted for vertical alignment, in compliance with the general architectural bias for the vertical as

canonical orientation. We presume that this bias refers to both a general reference frame reflecting the significance of the vertical in the real world (e.g. gravity) and a specifically architectural reference frame which relates to the interpretation of general orientation preferences in architecture.

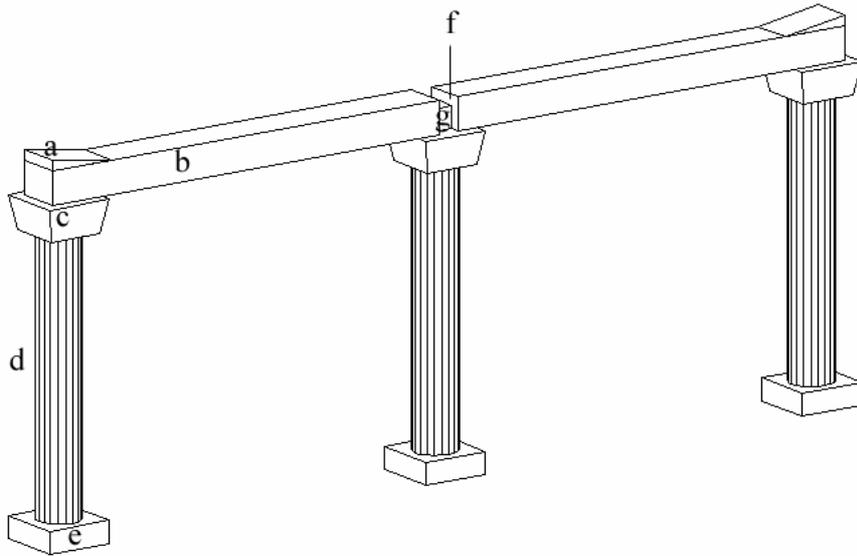


Figure 9. Coding of figure 7

On the basis of the above, the scene of figures 6, 7 and 9 can be coded as follows:

$a b \{c d e\} f g \{c d e\} f g b \{c d e\} a$   $(I = 17)$

$\langle \{c d e\} \rangle \langle (a b) (f g) (f g b) (a) \rangle$   $(I = 11)$

The use of distribution in the second version of the code makes explicit the grouping of the elements comprising the column, as well as the repetition of the group in the scene. This reflects the translational symmetry of the scene (colonnade). The bilateral symmetry that characterizes the total scene is largely lost because of the integrity of the elements and groups in the scene. Bilateral symmetry would be discovered in the code if line segments were used as primitives. This would have meant encoding of the outline of the elements rather than of the elements themselves and would permit splitting of a column into two symmetrical halves with respect to the vertical axis. However, the advantage of discovering and describing explicitly this accidental bilateral symmetry in a repetitive configuration such as a colonnade does not counterbalance the corresponding multiplication of structural information in the primitive code and the initial detachment from the reality of the perceived integral components / geons.

## 5. The evaluation of architectural formal goodness

Recognition-by-components and structural information theory provide the basis for:

- recognizing and representing the solid elements of an architectural scene;
- grouping the recognized elements in multiple alternative configurations;
- evaluating the alternative configurations with respect to coding efficiency; and
- establishing preference for one or two dominant configurations which represent the intuitively acceptable or plausible interpretations of the scene.

These operations link the representation of the built environment with perception and figural goodness. The necessary deviations from established conventional architectural representations reflect the choice of general cognitive and perceptual theories as the starting point of the investigation. It is proposed that architectural representations and in particular (a) the use of outlines to denote solid entities and spaces and (b) the deterministic decomposition into known components should be reconsidered with respect to the recognition-by-components theory and related vision research. The addition of a memory component to structural information theory would facilitate transition from the basic level of the primitive and end codes to known configurations denoting familiar objects.

The representation of spaces remains a problem that deserves particular attention and further research. The use of outlines, as in figure 5, is the obvious starting point, as it conforms to the way we read floor plans and other conventional representations and to existing computational representations such as rectangular arrangements and shape grammars. This would allow for an exploration of structural information theory and recognition-by-components in the application areas of these representations. From a cognitive point of view, however, the outline of a space in two or three dimensions might not be a relevant or meaningful representation. It has been proposed that surfaces could form a representation level that not only links higher with lower vision (Nakayama, He et al. 1995) but also agrees with the Gibsonian perception of space in terms of surfaces which fill space (Gibson 1966). This view is entirely different from the mainstream Euclidean co-ordinate organization of perceived space whereby the two dimensional retinal image is enriched with depth information derived primarily from binocular disparity. Perception of space in terms of surfaces stresses the biological and ecological relevance of these surfaces as containers of different actions and as subjects of their planning. One example of this relevance is locomotion for the ground surface and related generally horizontal surfaces.

Another issue that requires further consideration concerns the essentially bottom-up character of both recognition-by-components and structural information theory. The addition of a memory component to the system, i.e. a database of geon configurations corresponding to known, familiar entities, would facilitate processing of information at the basic levels and permit rapid transition to the higher levels of the representation. As these configurations would represent compact structures with respect to structural

information, we assume that exposure to and recognition of similar or equivalent scenes leads to the transformation of earlier experience into memories which influence our understanding and aesthetic evaluation (Scha and Bod 1993).

The validity of the combination of structural information theory and recognition-by-components for aesthetic analysis is beyond the scope of this paper and subject to further research and empirical analysis. The correspondences between intuitive aesthetic factors, e.g. as formulated in Birkhoff's aesthetic measure, and the coding operations of structural information theory suggest that this approach to perceptual organization is capable of supporting analysis in a coherent manner lacking in studies which employ perceptual organization as an explanation of isolated aesthetic principles.

The representations produced by the combination appear to hold for perception in general and for figural goodness. The transition to aesthetic appreciation is based on the significance of redundancy, as well as to the explicitness of factors which determine our judgements about perceived objects. In architecture the aesthetic contribution of redundancy has been interpreted both positively and negatively. Following the reference frame hypothesis, we may assume that redundancy refers to preferences organized in external (cultural) reference frames which attach different values to complexity and minimal coding. It is conceivable that redundancy is a positive aesthetic factor in one aesthetic system and negative in another. While this is normally only implicit in the system, a closer investigation of the corresponding reference frames reveals it through the significance of coding operations such as repetition and symmetry. The same reference frames reveal other principles which relate to perceptual organization, such as the formalist bias towards "functional expression", i.e. the association of certain elements with specific use types and the signification of concrete affordances in the form of the elements, including the coincidence of different aspects such as formal articulation and structural organization (Holgate 1992).

Finally, it should be noted that the information content of a description relies heavily on the primitives of the representation and hence on the abstraction level that has been chosen for it. In the framework of the multilevel representations of computer vision (Marr 1982; Rosenfeld 1984; Rosenfeld 1990) there is scope for considering the figural goodness and the information content of an object at different abstraction levels. The same applies to architecture, where different abstraction levels not only eliminate details that may be unwanted in e.g. the comparison of a classical and an modernist building while retaining the spatial organization of the designs, but also support correlation of local relationships into coordinating devices which accept interchangeable elements (Koutamanis 1996; Koutamanis 1997).

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