Linking building-circulation typology and wayfinding: Design, spatial analysis, and anticipated wayfinding difficulty of circulation types

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Abstract

Understanding how people interpret building circulation is a critical topic for architectural design and post-occupancy evaluation. However, few studies have examined relationships between architectural circulation and human wayfinding processes, such as spatial complexity and wayfinding difficulty. To assess these, we propose a cognitive–architectural description of circulation typology. Based on a prominent architectural case, the Amsterdam Municipal Orphanage designed by Aldo van Eyck, we explore a graph-based method to create systematically modified building layouts. We develop three distinct circulation types, linear, curved, and grid-based, which differ in their geometrical structure but are comparable in their functional and topological organizations. To identify the structural differences between these circulation types, we conduct an objective spatial analysis of layout visibility and examine subjective judgments of anticipated wayfinding difficulty. Based on the subjective judgments, the linear circulation is the easiest of the three and the grid-based the most difficult, while the curved circulation is intermediate. This is only partially in line with the results of the objective analyses. Hence, we conclude that further behavioural validation of wayfinding difficulties is needed to clarify our findings.

Keywords:

Circulation typology; anticipated wayfinding; spatial cognition; space syntax; architectural design research

1. Introduction

The idea of movement through space is one of the central themes in architectural theory, design, and practice. Le Corbusier suggested that to ‘experience architectural space truthfully, it is necessary to walk about and through the building’ (Le Corbusier, 1962, p.30, authors’ translation). In other words, architectural shapes and building layouts are revealed literally step by step.

A building’s circulation is the key factor organizing its layout, and hence is of interest for both architects and other professionals involved in post-occupancy evaluation. One prerequisite for linking circulation types with wayfinding performance is to establish a formal method of description that a) creates a link between building circulation and wayfinding difficulty and b) explores new ways of formally analysing different types of building configurations. We argue that such a method can be developed through analysis of a spatial typology of circulation types. To achieve this, we combine two complementary methods: spatial analysis (mainly space syntax), and ratings of anticipated wayfinding difficulty based on floor-plan evaluations. If a connection exists between the two methods, the spatial measures could be used predictively (Butler et al., 1993; O’Neill, 1991; Weisman, 1981).

First, we identify ‘circulation types’: prototypical configurations that organize the layout of a building. Then, we develop a method for systematically varying building circulation and apply it to an existing architectural layout, thus constructing examples of the various circulation types. The resulting circulation variations differ in structures but remain comparable in their functional organization. Our intention is to contribute methodologically and theoretically to understanding how different building circulation types can be analysed and how floor-plan analyses can predict wayfinding difficulties based on the circulation typology.

2. Background

2.1. Spatial configuration, circulation, and wayfinding

Wayfinding consists not only of locomotion but also of manifold cognitive processes (Golledge, 1999; Montello, 2005). The configuration of space and visual accessibility between locations are central factors that influence how easy or hard it is to identify routes within a building (Kuliga et al., 2019). In most wayfinding situations, the destinations are not directly visible (e.g. when configurational elements such as walls block the wayfinder's view). Wayfinders typically need to reason about the relationships between different parts of a space to understand a building's spatial configuration (Montello, 2005).

Spatial analysis that examines spatial configuration and visual accessibility has largely been associated with being able to predict both locomotion and wayfinding decisions (e.g., Haq & Zimring, 2003; Hölscher et al., 2006; Li & Klippel, 2012). Consequently, spatial analyses are especially valuable for architects and planners, who may seek to evaluate the wayfinding difficulty of their designs based solely on floor-plan analyses. In our work, we thus focus on anticipated wayfinding difficulties using floor-plan analysis.

However, it is not entirely clear how building circulation types affect the ease or difficulty of wayfinding. For instance, Passini (1996) suggested that good form based on Gestalt principles (cf. Koffka, 1935; Köhler, 1929) contributes to wayfinding performance. Good form is easily appraised, and once the ordering principle has been grasped, it can support understanding the complexity of a layout and can then be used to inform wayfinding decisions. This observation is reinforced by Montello (2007, p.3) who suggested that

> the overall shape or ‘gestalt’ of a path layout can determine whether a particular element is disorienting… Layouts may be said to vary in their closeness to a ‘good form’; comprehending a layout is easier when the layout has an overall pattern that can be apprehended as a single simple shape, perhaps allowing easy categorization. A square has better form than a rhombus; a circle has better form than a lopsided oval.

Similarly, O’Neill (1991) reported that participants respond to good form when rating the spatial complexity of architectural plans.

However, as circulation types have been assessed rather informally, no accepted typology of building circulation exists. Moreover, most architectural settings are not based on a single pattern but comprise combinations of circulation types. These can be constructed from various geometric rules or by combining elements from the different types. However, Passini (1983) found that people facing a composite layout tend to mentally extract a single organizational principle and then interpret the whole setting according to this perception.

2.2. Circulation types

In this study, we focus explicitly on simple, two-dimensional geometric shapes to illustrate their general principles of spatial organization. Based on Arthur and Passini’s work (1992), we develop a description of circulation typology by defining the physical characteristics of circulation systems. We limit our classification to three major types and illustrate the typology with a set of prominent architectural cases[1] (to explore other typologies, the reader is addressed to Ching, 1996; Cousin, 1980, von Meiss, 1986; and Steadman, 2014).

The most fundamental circulation type is a *linear* layout as it allows the greatest number of straight views (Hillier, 1996). Linearity extends from an ordered linear path to a random or axial layout (Figure 1). This circulation, as any other circulation type, can have various spatial characteristics; it may be wide or narrow, short or long, and so on. The linear system can differ in having single or multiple circulation channels and symmetry in the organization of its functional units.

Figure 1

The next type of circulation is a *curved* system, which is structured by central symmetry or rotation. It varies from focal to concentric and spiral patterns (Figure 2). This curved circulation is characterized by a central space around which functional units are organized. The circulation in these buildings is related to the central space. Central space here is meant as an organizing

[1] In addition to the classification of the floor circulation patterns, circulation is differentiated by *horizontal* or *vertical* directions (cf. Kuliga et al., 2019; Hölscher et al., 2012; and Hölscher & Brösamle, 2007). The scope of this study is limited to horizontal circulation patterns, since the horizontal circulation system is primary; it determines the entire structure and the basic shape of the building.

force that provides a sense of orientation along a circular movement. In the case of curved spatial organization, the movement is a result of rotation with a specified radius.

Figure 2

Visual contact with a central, focal point, as in the case of the Guggenheim Museum (Figure 2a), allows the maintenance of directional references. Without contact with the centre, wayfinding can become confused following several turns (Arthur & Passini, 1992).

The last of our circulation types is a *grid-based* or network system. This system evolved by repetition of a dominant pattern across different scales. It can be based on a grid, scatter-point, or hierarchical network (Figure 3). Spatial units in this system follow a certain coordination structure. In addition to the coordinated grid, such circulation can be based on a nested space system that is described by a sequence of units going from the largest to the smallest.

Figure 3

2.3. Case study: The Municipal Orphanage

We use the Amsterdam Municipal Orphanage, designed by Aldo van Eyck between 1955 and 1957, as a case study due to the complex arrangement of the spaces within its layout. In contrast to traditional institutional buildings, the Orphanage does not order its functions hierarchically in a static composition governed by a central axis but unites a multiplicity of intersecting architectural volumes in one complex relationship (Figure 4).

Figure 4

The architect said of his design that

> the building was conceived as a configuration of intermediary places clearly defined. This does not imply continual transition or endless postponement with respect to place and occasion. On the contrary, it implies a break away from the contemporary concept (call it sickness) of spatial continuity and the tendency to erase every articulation between spaces, i.e., between outside and inside, between one space and another. Instead, I tried to articulate the transition by means of defined in-between places which induce simultaneous awareness of what is signified on either side. (Aldo van Eyck, in Kultermann, 1993, p.138).

The building can be described as a 'tiny city' roofed with many small and a few large domes (Kultermann, 1993). It consists of four units grouped along corridors (Figure 4d). The units are based on the same prototype, which in each case is elaborated with specific facilities according to the age of its residents.

The Orphanage's composition is formed by a grid, and the building circulation can be defined as a grid-based system:

> From the central 'piazza,' two interior 'streets' are branched out in fluctuated movement to give access via interior and exterior patios to the various units. This solution joins up an obvious economy with optimum prospect - these are streets, whose right-angled meandering relieves them from any central control. Their orthogonal zigzagging evokes a diagonal movement even though they are devoid of diagonal lines. Following this zigzagging, the residential units are unfolded and shifted in relation to each other along these streets. Their cohesion lies largely in the

central movement which they share. In this way, the building embodies both a stable and a dynamic conception of space, both central and dispersed (Strauven, 1996).

2.4. Representation and evaluation of spatial complexity

The literature on how spatial organization may be represented by certain types of information graphics is extensive, especially in studies on the perception and analysis of architectural space. Examples to assess spatial complexity include isovist analysis (Benedikt, 1979), linear representation of spatial configuration (Peponis et al., 1998), visibility and axial graphs (Turner et al., 2001; Turner & Penn et al., 1999), and the Inter Connection Density (ICD) measure (O'Neill, 1991).

Mathematical graphs are one of the most popular representations that allow spatial relationships to be systematized (Barthelemy, 2011). Graphs can be shown diagrammatically or represented as matrices, using well-known mathematical operations on a matrix for analysis. Graphs incorporate behavioural aspects in one framework with spatio-configurational ones and are simple and efficient (Dalton, 2005; Weener, 2000).

A graph is denoted as a pair where N is the set of nodes (vertices), $N = \{n_1, n_2, \ldots n_n\}$ and L is the set of links (edges), (see e.g., Gross & Yellen, 1999, for a comprehensive introduction to graph theory). A graph is represented by an adjacency matrix A, where

$$A_{ij} = \begin{cases} 1, \text{the nodes } n_i \text{ and } n_j \text{ are connected,} \\ 0, \text{otherwise.} \end{cases} \qquad (1)$$

To encode the spatial layout of the Orphanage, we chose to use a *boundary graph,* a graph that connects bounded spatial units and reflects their topological relationships (Hillier et al., 1984a). The graph is constructed from the main distinguishing features of any circulation system, the programmatic spatial units, and the intersections, creating several options for movement.

To evaluate newly created spatial layouts, we use the space syntax technique, which originally emerged in the field of architecture (Hillier & Hanson, 1983b). The space syntax axial map, convex map, and visibility graph are related to the visual accessibility of the layout. The axial map is built from unrestricted lines of sight, and the equivalent axial description of the building consists of the fewest and longest lines of sight that pass through every space. The convex map consists of space as a discrete spatial unit, of which the bounding polygon contains no reflex-angled internal corners. Therefore, all points within such a space are visible from all others (Hillier and Hanson, 1984). Visibility graph analysis (VGA) imposes a grid of points on the plan of a building and extracts visibility relationships between the points that are analysed as a graph, using each point as a node and mutual visibility as links (Turner, 2001; Turner & Penn, 1999). Generally, any architectural feature that reduces the clarity and complexity of the layout could discourage wayfinding, but this is only the case for a subset of space syntax measures identified in the wayfinding literature as establishing direct connections (Haq & Zimring, 2003; Hölscher et al., 2006).

Following the preliminary study, in which we examined various spatial techniques (Natapov et al., 2015), we chose the VGA over other space syntax methods because it allowed us to take the detailed geometry of the layout into account. The new circulation types retained the straightforward geometric measures, such as a units' area, perimeter, proportions, and orientation.

To compare the spatial complexity of the circulation types, we refer to the uniform space syntax measure of *intelligibility*, a relation between the local property of a place and its global properties. Intelligibility is defined as ‘the degree to which we can see from the spaces that make up the system’ (Hillier, 1996). Intelligibility is calculated as a correlation between two values, *connectivity* and *integration*.

Connectivity is a local property of a point. It calculates the number of nodes or grid points that interconnect with a given node. It captures how many destinations can be seen from each grid point.

Integration is the global relationship of a point to the whole system. It measures how many steps are required to access every other point in the layout from a given one (Hillier & Hanson, 1984). Integration determines the relative importance of the point within the visibility graph: its overall visual accessibility. The more integrated places with short distances to others have larger integration values.

It is important to note that connectivity shows how much one can see directly from one location, while integration shows how much one can see both directly and indirectly from the location. Intelligibility has shown high accuracy in predicting movement activity in cities (Jiang & Claramunt, 2004; Penn, 2003) and in buildings (Haq & Zimring, 2003).

3. Methods

We used the three basic types introduced in the previous sections: grid-based, linear and curved.

Based on the boundary graph method, we encoded the spatial layout of the Orphanage to develop the corresponding circulation alterations and assessed them with VGA spatial analysis and subjective evaluation. First, we altered and simplified the original layout. Second, we modified the existing, complex circulation (grid system) into a linear and a curved version.

We hypothesize that the grid-based circulation will be rated as most difficult in spatial complexity and anticipated wayfinding difficulty, given its hierarchy of room clusters around central yet zig-zagged hallways. We expect that participants will rate the linear layout as easiest in spatial complexity and anticipated wayfinding difficulty, since it provides a clear, axial line hallway around which the rooms are arranged. The curved layout is expected to be intermediate as it fulfils rules similar to the linear but does so in a constant rotation, which is probably more difficult to comprehend once people move though the building.

3.1. Preparation work and graph-based systematic redesigns

First, we identified the main circulation space and the boundaries of the existing spatial units defined by the entrances in the layout of the Orphanage. The term ‘spatial unit’ corresponds to a room in the building, and they serve as nodes (N) in the boundary graph. A room generally means a fully enclosed space boundary with or without doors that is defined by a bounded wall perimeter. Links in the graph (L) are entrances between the spatial units (Figure 5).

Figure 5

Therefore, the boundary graph represents the existing building and encodes the topological relations between the building’s spatial units as the sequence of the units’ connection. Consequently, we use the Orphanage’s complex geometry to develop the new circulation layouts.

3.2. Grid-based circulation

Figure 6a shows a boundary graph overlapping with the original layout of the Orphanage. Ithas diverse components: elements of physical construction, decorative objects, textures, materials, and so forth. Initially, we found it nearly impossible to reduce them all to a limited set of features. However, for circulation alone, we were able to limit the variety of building features needed for the sequential boundary graph.

First, we prepared the ground plan by turning all the walls and partitions to solids regardless of the original material. The building plan was reduced to rooms and corridors with no indication of the building envelope or other spatial subdivisions. We simplified the plan by eliminating all the elements of the vertical circulation, such as staircases and ramps. We also deleted small partitions and built-in furniture. Moreover, we gave all the openings a uniform width.

Figure 6

After simplification of the building plan, we identified the functional units, nodes in our graph (N) and assigned with the numbers for identification (ID). Figure 6b shows the resulting non-georeferenced boundary graph with the original order of the units in the main circulation space. A fundamental issue in building circulation is the specific paths that people take when moving from one space to another. Therefore, the sequence in which the units are connected is important.

3.3. Linear and curved circulations

Based on the extracted graph of the topological relations between the functional units (Figure 6b), we developed a linear version of the circulation.

The original building has a strong hierarchy of major and minor corridors in a composite style; in the linear layout, the main circulation space was straightened into a line in which the hierarchy of the units' clusters is the same as the grid-based circulation, but the wayfinding is not. The circulation space of the building, the major and minor corridors, was transformed into a linear path. The branched corridor, which originally formed a tree-like shape, is straightened to achieve maximum linearity (Figure 7a). In addition to the modification of the main corridor, the connections between other branched units are ‘unfolded’ and straightened as much as possible. During the modification, the rooms’ areas and all other parameters, such as the height and the width, were kept unchanged. However, in some cases, we rotated the units to maximize the linearity of the overall composition. Several rooms in the original layout are patios (Figure 4d); they are preserved as patios in the linear layout.

Figure 7

During the modification process, our single aim was to accomplish a spatial organization of the building circulation with limited concern for building design, aesthetics, or function. Following the preliminary study of the circulation types (Natapov et al., 2015), the last variant is the curved one. We developed this system in such a way that the major and the minor corridors generate circular movement while keeping the order of connections and topological relations unchanged (Figure 7b). The connections between the branched units are altered, where possible, to be circular as well, in order to reinforce a circularity of movement. Existing patios, room areas, and other attributes are preserved as in the original building as far as possible. It is worth noting that the architectural qualities of the original building were sacrificed in the new versions for the sake of an artificial geometry. Figure 8 presents the three final circulation types.

Figure 8

3.4. Objective and subjective evaluations of spatial complexity

Our evaluation methods include an objective spatial analysis using VGA and a questionnaire gathering subjective judgements from a group of participants. VGA identifies the structural differences between the layouts in visibility and wayfinding, and the questionnaire measures the subjective anticipated wayfinding difficulty of the layout variants. If connection between objective and subjective outcomes exists, the objective measures could be used predicatively in architectural planning.

For the custom-made questionnaire, three floor-plan layouts were printed in black-and-white A5 images on A4 paper: an original, simplified layout that closely resembles the real building, a linear layout, and a curved one. A total of 54 participants were first asked to study the original floor plan and to imagine that they were standing inside the building. Participants were not allowed to turn pages to compare individual layouts. Then, the participants were invited to rate how complex the layout of the building was on a 1-7 Likert scale from very simple to very complex and to comment on their decision (‘spatial complexity’). Participants also rated how easy it would be to find one’s way around a building (1-7, easy to difficult, ‘anticipated wayfinding difficulty’). We also asked for participants’ ratings of each layout’s visual appeal, as architects typically are interested not only in functional aspects but also in whether their layout is visually appealing (1-7, appealing to not appealing, ‘visual appeal’). Afterwards, to control for order-of-presentation effects, one group of participants (n=27) rated the linear floor-plan layout first, and subsequently the curved layout, using the same three questions. The other group (n=27) rated the curved layout and then the linear layout, with the same questions. Finally, all participants were shown the three layouts again as three A6 images on an A4 page. Participants were asked to compare the layouts and rank them for anticipated wayfinding difficulty. Finally, they were asked to comment informally on their decision.

4. Results

4.1. Objective evaluations of spatial complexity

The results of the VGA local and global properties across the three layouts are presented in Figure 9. Figures 9a, 9c, and 9e present a measure of VGA connectivity, and Figures 9b, 9d, and 9f present a measure of VGA integration.

Figure 9

The distribution of the integration values of the grid layout presented in Figure 9b highlights particular parts of the main patio and the corridors with the highest visibility rank in comparison to the connectivity measures of the same layout. The results of the two measures in the linear layout (Figures 9c and 9d) are intuitively clear: the long linear corridor and the entrance hall at its very beginning are the most visible parts of the setting. In Figures 9e and 9f, the results of the connectivity and the integration of the curved layout exhibit low visibility and demonstrate that the layout lacks a strong centre that could attract a wayfinder's gaze. The circular shape of the corridor and an inaccessible void in the centre prevent proximity and integration.

Although the three circulation alternatives share the same topological graph, they differ significantly in their spatial complexity, size, and space. To compare their spatial complexity, the intelligibility measure was calculated to correlate the local property, connectivity, with the global property, integration (Table 1). These measures are compared in section 4.3 with the subjective measure of anticipated wayfinding difficulty.

Table 1

4.2. Participants' details and subjective evaluations

All 54 participants filled in our pen-and-paper questionnaire that investigated subjectively anticipated wayfinding difficulties based on floorplans plan-views of the circulation types that we created. The participants' age ranged between 19 and 35 years (*M*=25.48, *SD*=4.01), and 31 participants were female. All the participants were students: 34 studied architecture and 20 cognitive science. When controlling for architectural experience, we found a correlation between higher experience and lower ratings of the complexity of the linear layout (r (47) =-.66, p<.001) and anticipated wayfinding difficulty (r (47) =-.50, p<.001). Since there were no statistical differences between the groups given differing orders of presentation, the groups' responses were combined for further analysis.

Table 2 summarizes the results for the pairwise comparisons of the ratings for the layouts: Participants rated the grid-based layout as significantly more complex than either the curved or the linear layout. The linear layout was rated as significantly less complex than the curved layout.

The grid-based layout was rated as significantly more difficult for wayfinding than either the curved or the linear layouts. The linear layout was rated as significantly less difficult for wayfinding than the other two layouts.

The grid-based layout was less appealing than either the curved or the linear layout. There were no differences between the visual appeal of the curved and the linear layouts.

Table 2

Moreover, based on the rank data, chi-square testing revealed that the layouts were ranked significantly differently for anticipated wayfinding difficulty (*M*=2.17, *SD*=.55); Pearson's Chi-square χ^2 (2, 53)=30.83, p<.001) as well as its reverse, the ease of wayfinding (M=1.60, SD=.93;

χ^2 (1, *53)*=8.32, *p<.01*), while the answers for intermediate ratings were equally distributed (*M=2*.21, *SD*=.81, χ^2 *(*2, 53*)*=3.66, *p*=.16). These rankings align with the ratings above.

The difference in the distribution of these frequencies was significant (χ^2 (4, 53) =106.00, *p*<.001). The majority of the participants (37) ranked the linear layout as easiest, followed by 13 participants who rated the curved layout as easiest, and 4 participants who ranked the grid-based layout as easiest. Unsurprisingly, the reverse pattern was evident in the most difficult layout for wayfinding: 37 participants ranked the grid-based layout as most difficult and 16 the curved layout, but no one attributed a 'most difficult' rank to the linear layout. The rankings of anticipated wayfinding difficulty showed that 24 participants ranked the curved as intermediate, 16 the linear, and 13 the grid-based layout.

4.3. Informal results

Table 3 presents a summary of the key topics that participants mentioned as reasons for their ratings. The comments were selected informally by the authors by categorizing content into the three predefined categories (i.e., spatial complexity, anticipated wayfinding difficulty, visual appeal).

Table 3

Participants generally rated the linear layout most intelligible, containing clear order and good form with a central axis that provides orientation. However, its visual appeal was rated as rather simplistic and dull. Some of the participants' comments for the linear layout were 'Imagine yourself going through, checking each location until a target is reached'; 'in this building you have one route-direct access to most points'; 'the end and the beginning of the path is clear'; and 'the linear is the most structured, having four obvious directions.'

The grid-based layout was evaluated as the most difficult for wayfinding and the most complex, likely due to low visual access, spatial ambiguity, and spatial complexity. Yet, in contrast to the ranking some participants described its visual appeal as ‘beautiful’; ‘interesting’; and ‘having a good balance and a nice composition.’ Comments addressing the grid-based layout suggested that it ‘has too many turns and no main path’; ‘has many repetitive and very similar paths’; and ‘the connections between rooms are complex.’

The curved layout was described as hierarchical yet ambiguous, in which the constant rotation was described as a crucial confusing factor in wayfinding. The visual appeal of the curved layout was described as unbalanced yet interesting. Some of the participants said that movement in this building would involve constant rotation, causing ambiguity and confusion. Others emphasized a lack of visual contact with the central space, which would create a gap in the experience of the building. Assessing the visual appearance of the curved layout, the participants stated that it looked ‘not balanced’ and ‘not practical’ together with being ‘nice’ and ‘fun looking.’

4.4. Comparison of the objective and subjective test results

We found that participants’ subjective evaluations align only partially with the results from the spatial analysis (i.e., we found the highest value of intelligibility in the linear, followed by the grid-based, and then the curved layout). Yet, participants rated the grid-based, rather than the curved layout as the most complex, as most difficult for wayfinding, and as least appealing (based on the questionnaire; in the informal comments, some participants found the grid-based layout appealing), despite the lower intelligibility value of the curved layout. Table 4 presents the comparisons between the objective intelligibility measures and the subjective evaluations of the anticipated wayfinding difficulty.

Thus, the results do not give a clear answer which layout is more difficult for wayfinding. Consequently, in the discussion section, we suggest a behavioural validation to shed more light on this misalignment between spatial analyses and the ratings.

Table 4

5. Discussion

In this study, we assessed potential links between circulation types, spatial complexity, anticipated wayfinding difficulty, and visual appeal. The results mainly reflected how elements of spatial organization, such as layout topology and visibility, impacted subjectively rated anticipated wayfinding difficulty.

First, from an existing, complex grid-based layout, two new circulation types were created: a linear and a curved. Second, the floor plans of these artificial redesigns were evaluated with both objective syntactic measures and subjective ratings of spatial complexity, anticipated wayfinding difficulty, and visual appeal.

Both objective syntactic VGA and subjective responses identified the linear layout as ‘the easiest’ in terms of spatial complexity. This layout is based on a simple, visibly clear straight axis. Movement in this layout occurs along the main corridor from point to point, and its spatial arrangement is expected to minimize spatial complexity. This result provides support for the space syntax method, which treats spatial arrangements as the longest lines of sight, confirming that people feel comfortable following the longest sightline that leads to where they are heading.

The answer to the question, which of the circulation types can be considered ‘the most difficult’ for wayfinding differs depending on whether the objective spatial analyses or the subjective evaluations are considered. In this way, spatial complexity related to wayfinding difficulty in a different way than we expected: the most complex layout based on spatial analysis was not perceived as most complex. For the grid and the curved types, the VGA appears to be only partially relevant in predicting ratings for anticipated wayfinding difficulty. Participants rated the original, grid-based layout as the most difficult for wayfinding, but it was estimated only as intermediate by VGA analysis. The grid-based layout has a hierarchical tree-like structure that in theory could facilitate movement. However, participants felt that it had many turns and directional changes, and these could be a source of wayfinding errors. The curved layout generates continual rotation that could cause ambiguity and confusion and lacks any hierarchy that might help a wayfinder. However, participants felt that its simpler general organization can be easily appraised; this might contribute to easier wayfinding.

The visual appeal of the layouts elicited another pattern of response. The original, grid-based layout was rated less appealing than either the curved or the linear layout, while no differences were found between the visual appeal of these two layouts. Thus, the subjectively rated visual appeal seems hard to capture based solely on a floor-plan analysis.

One cause of this might be differences in individual visual preferences, which we did not assess in the current study set-up.

These results also demonstrate the potential limitations of our method: analysis of subjective ratings based on two-dimensional plans can provide inconclusive results, since respondents need to immerse themselves from a plan-view into the egocentric, three-dimensional perspective of building users, as architects do during the building design process. Such analyses can only provide an approximation of expected spatial complexity and anticipated wayfinding difficulty; they reveal little about visual appeal. Additional spatial variations can be developed, as shown in

Natapov et al. (2015); in further research using virtual reality, we plan to present rooms on both sides of the curved version with views through the curved walls.

The current results can be regarded as a starting point for future research and behavioural validation that includes assessing wayfinding performance in these circulation types. Such validation should include a behavioural experiment in a virtual reality laboratory. The study that we envision will assess additional factors that influence the ease or difficulty of wayfinding, such as participants' wayfinding strategies, sense of orientation, individual spatial skills, and aesthetic or emotional responses to variations of these building circulation types.

A key strength of the current study is a systematic implementation of the graph method to encode the spatial organization of an existing building. This method extracts topological relations between the building's functional units and allows us to successfully transform its original layouts into well-controlled variations that allow assessment of diverse circulation typologies.

In conclusion, although buildings are typically much more complex and consist of combined circulation systems, our study provides insight into how the architectural forms of circulation spaces impact spatial complexity and wayfinding difficulty.

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Tables

Grid	Linear	Curved
$R^2 = .45$	$R^2 = .63$	$R^2 = .32$

Table 1 Intelligibility (linear correlation between connectivity and integration) of the three circulation modifications.

Question (and scale)	Circulation type	*M*	*SD*
Spatial complexity:	'Grid'	5.39	1.280
How complex was the layout of this building?	‘Linear’	2.67	1.374
(simple <(1-7)> complex)	‘Curved’	4.17	1.778
Anticipated wayfinding difficulty:	‘Grid’	5.44	1.284
How easy would it be to find one’s way around a building	‘Linear’	2.39	1.352
with this layout?	‘Curved’	4.31	1.882
(easy < (1-7)> difficult)			
Visual appeal:	‘Grid’	5.22	1.269
How visually appealing is this layout for you?	‘Linear’	3.89	1.121
(appealing < (1-7)> not appealing)	‘Curved’	3.87	1.372

		95% confidence interval				
Pairwise comparisons		Lower and Upper		*t*	*df*	Sig (*p*)
Spatial complexity	Grid vs. Curved	.54	1.91	3.58	53	.001
	Curved vs. Linear	.82	2.18	4.41	53	< .001
	Grid vs. Linear	2.26	3.19	11.70	53	< .001
Anticipated wayfinding difficulty	Grid vs. Curved	.45	1.81	3.35	53	.002
	Grid vs. Linear	2.52	3.58	11.54	53	< .001
	Curved vs. Linear	1.24	2.62	5.59	53	< .001

Visual appeal	Grid vs. Curved	.82	1.91	5.05	51	< .001
	Grid vs. Linear	.97	1.86	6.35	52	< .001
	Curved vs. Linear	-.48	.36	-.28	50	.78 (not significant)

Table 2 Summary of the ratings for the three circulation types.

Circulation type	Spatial complexity	Wayfinding rating	Visual appealing
Grid	• no clear order • looks like a maze due to zigzag hallways • high spatial complexity; clusters unclear • one hallway connects all rooms	• many turns • spatial ambiguity • no landmarks • hard to remember locations and rooms • dead ends • many small rooms	• beautiful • very good balance • nice composition
Linear	• very good structure • clear order, good form • based on central line • simple • good layout overview	• easy to orient • the main axis is visible from everywhere • symmetric • predictable, but rooms still difficult	• easy • boring • too simple
Curved	• everything is well connected • no good orientation • hierarchy organized around the circle is clear • no corners	• constant rotation is hard for orientation • no central space (‘no beginning and no ending’) • no landmarks	• nice • not balanced • not good organized • fun to look at • artificial

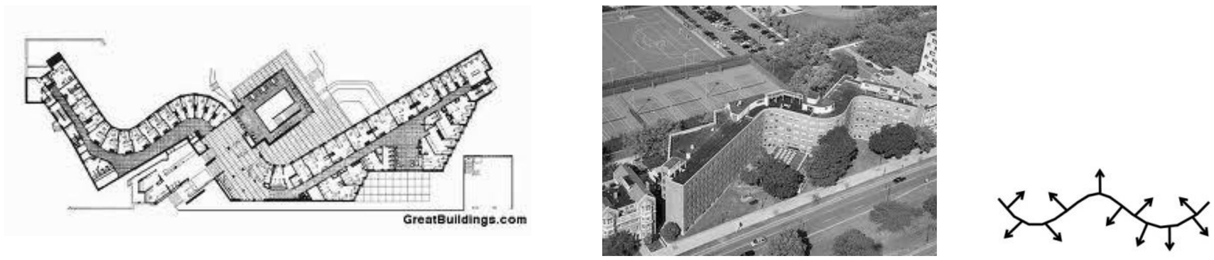
	• has one main route and clear access to the rooms • entrance unclear	• clear order • no dead ends • spatial ambiguity	• make a rolling floor in the middle and you could be carried everywhere • not practical

Table 3 Sorted list of the reasons provided by the participants.

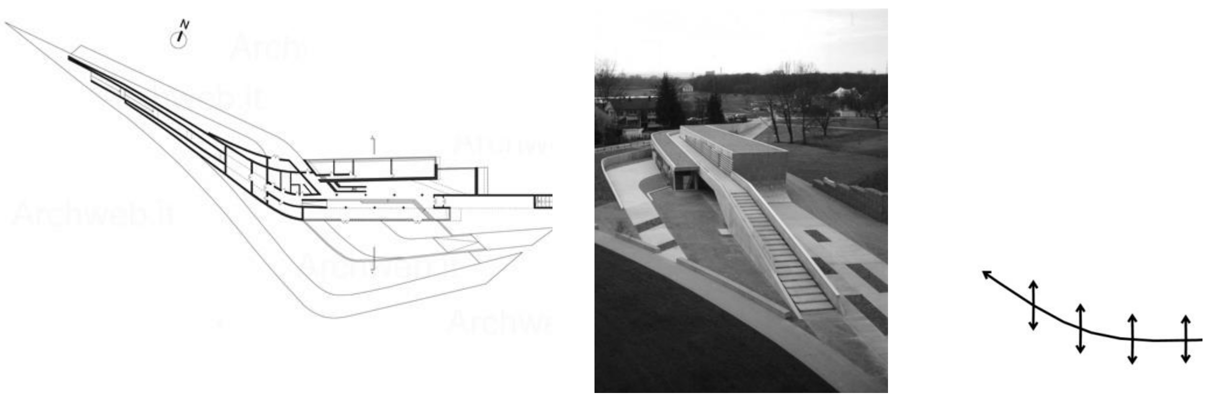
	Visual Intelligibility	Wayfinding Evaluation
Grid	.45	36 of 54 participants rated this layout as the ***most difficult***
Linear	.63	37 of 54 participants rated this layout as the ***easiest***
Curved	.32	24 of 54 participants rated this layout as the ***intermediate***

Table 4 Visual intelligibility and assessment of the anticipated wayfinding difficulty of the three types. Note that the value of 1 means that the layout is highly intelligible with a full, positive correlation between the local and the global visibility properties, whereas 0 means no correlation.

Figures



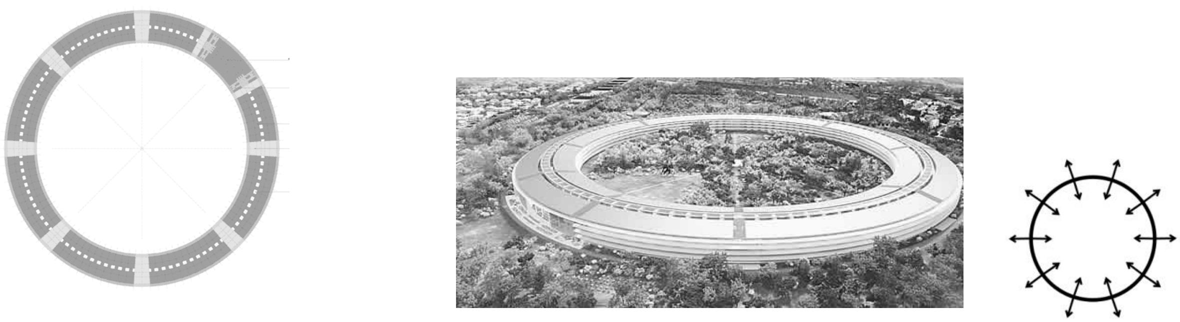
(a)



(b)

Figure 1 Various types of linear circulation: (a) a linear, serpentine path. Baker House, MIT, architect Alvar Alto, (Source: MIT List Visual Art Center); (b) a linear, bent path, Landscape Formation One, architect Zaha Hadid (Source: Zaha Hadid Architects.com).

(a)



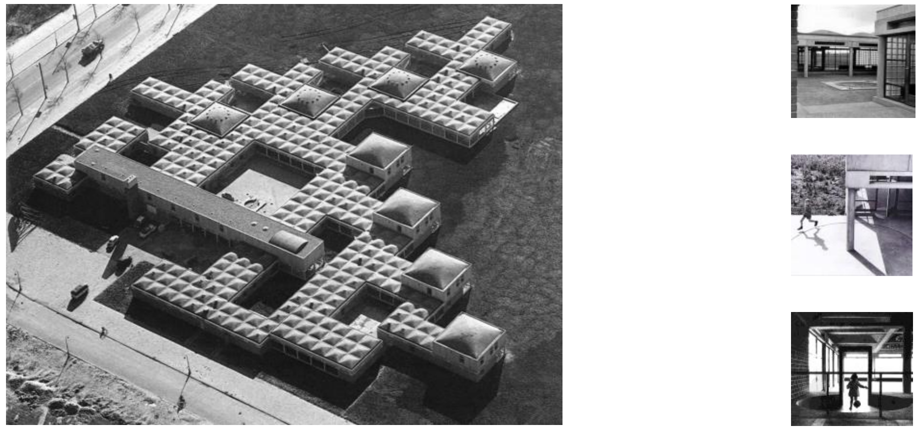
(b)

Figure 2 Various types of curved circulation systems: (a) a spiral, centralized path, Guggenheim Museum, architect F. L. Wright, (Source: Wright on the web.com); (b) a concentric path, Apple Partners 2, architects Foster& Partners (Source: Cupertino.org).

(a)

(b)

Figure 3 Various types of grid-based circulation systems: (a) grid, network path, The Israel Museum, architect Al Mansfeld, (Source: The Israel Museum, Jerusalem); (b) hierarchical network path, Place Desjardins, architects La Haye and Oulette. (Source: Desjardins Gestion Immobiliere Inc.)



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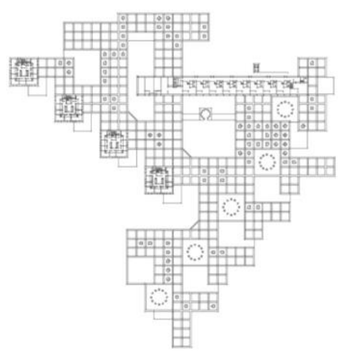
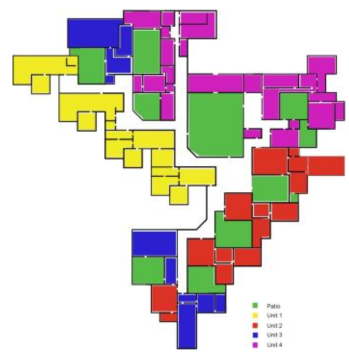
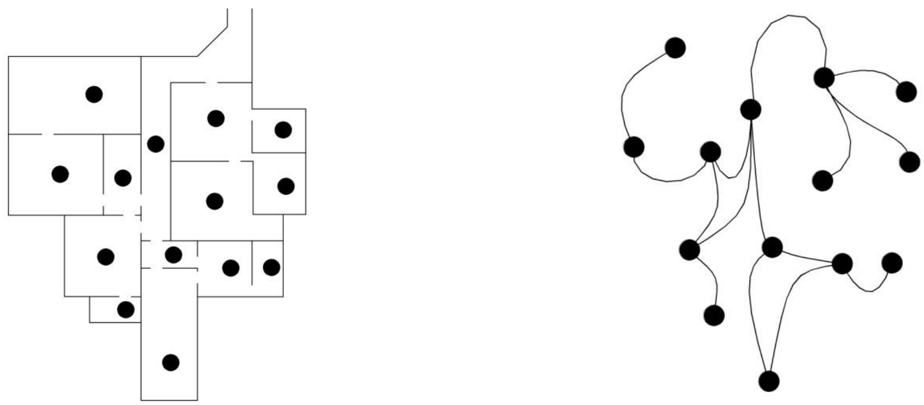




(b) (c) (d)

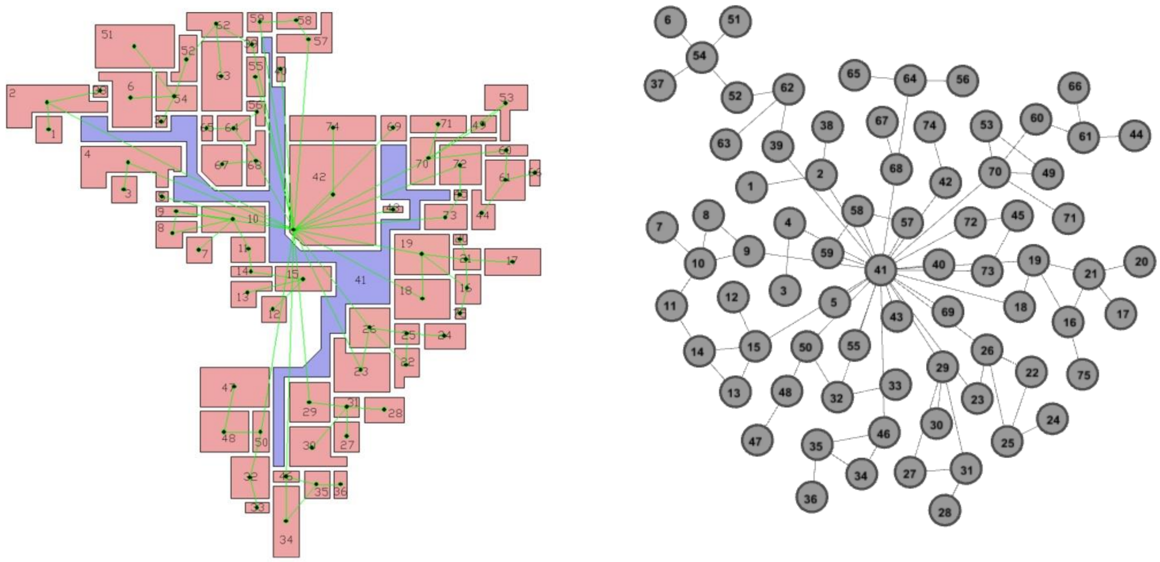
(e)

Figure 4 (a) Amsterdam Municipal Orphanage. Arch. Aldo van Eyck, (Source: ArchDaily.com, 2008-2014); (b) Ground floor plan; (c) First floor plan; (d) Functional scheme of the units in the original building; (e) Elevations (Source of images a, b, c and e, Weston, 2004).



(a) (b)

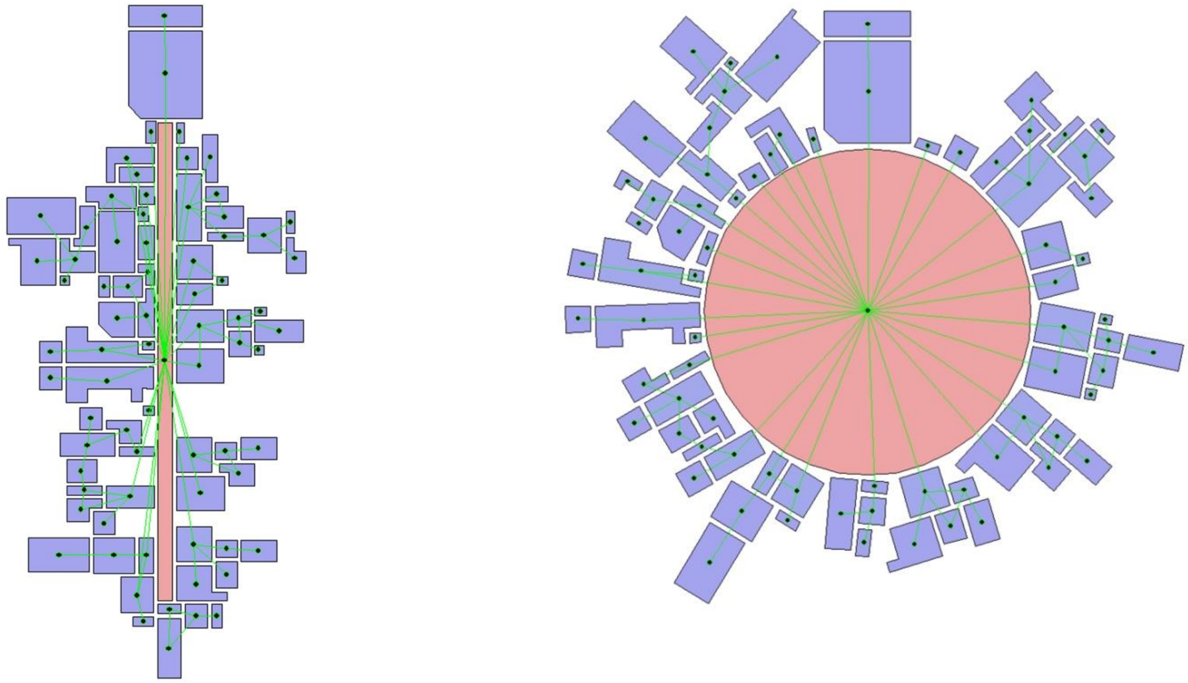
Figure 5 Illustration of the boundary graph construction; (a) detail of the plan view; (b) corresponding boundary graph. (Adapted from Hiller et al., 1984).



41>50|32|46|29|23|26|18|19|73(2)|72|70(2)|69|42|43(2)|42(2)|40|57|58|59|50|32|46|29|23|26|18|19|39|55|68|2|4(2)|5|9|15

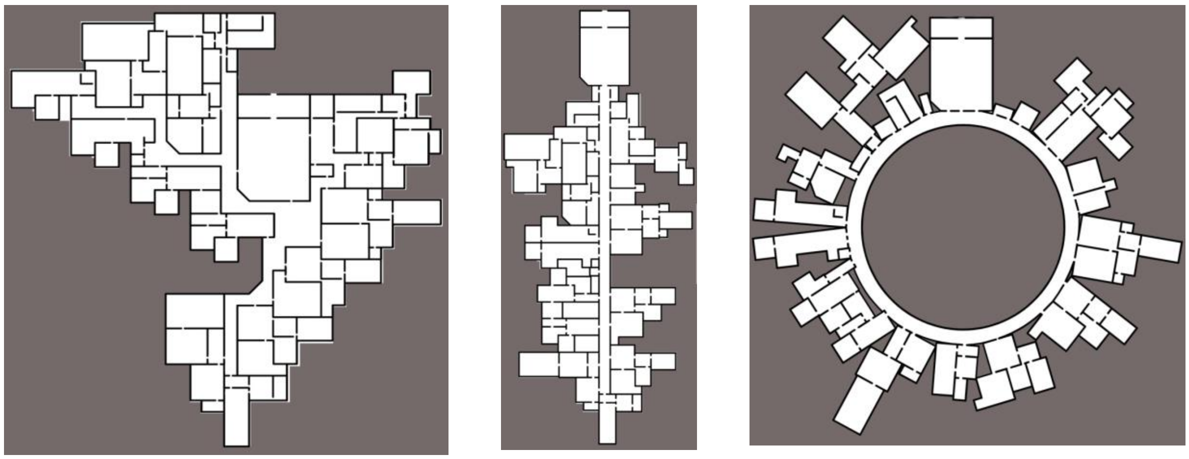
(a) (b)

Figure 6 (a) Space-boundary polygons of the grid-based circulation and its boundary graph, *Depthmap* software (Turner, 2001); (b) (a) Non-coordinated boundary graph and original order of unit connections to the main corridor with number of connections in brackets. (The graph was visualized in a network analysis package, *Gephi* (Jacomy et al., 2009).



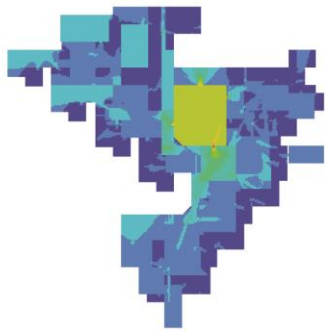
(a) (b)

Figure 7 Space-boundary polygons (a) of the linear circulation with overlapped boundary graph; (b) of the curved circulation and its boundary graph. (The concentric corridor is identified by the centroid: the geometric centre of the shape).

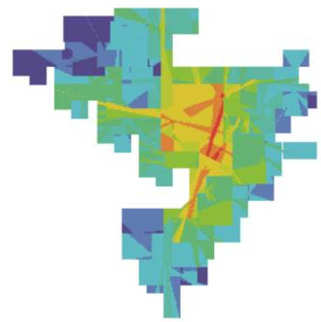


(a) (b) (c)

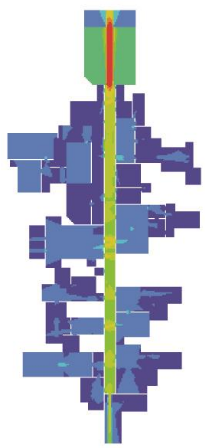
Figure 8 Circulation modifications; (a) grid-based circulation, (b) linear circulation, (c) curved circulation.



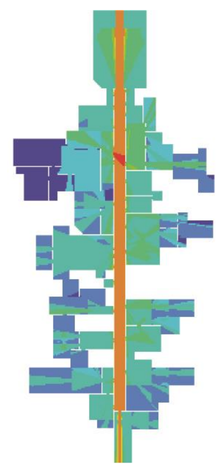
(a)



(b)



(c)



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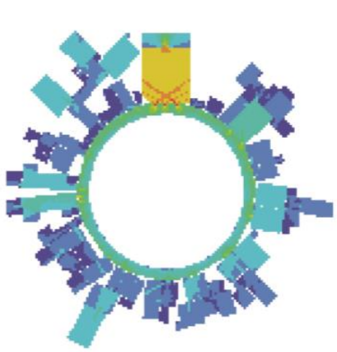

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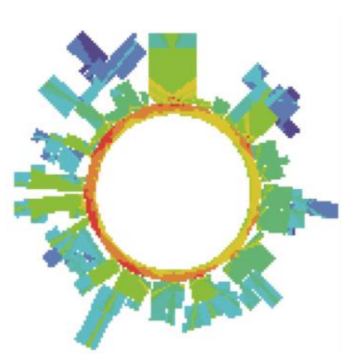

(f)

Figure 9 (a) Visibility Graph Analysis; (a) grid-based circulation system, coloured by connectivity (high by red and low by blue); (b) grid-based circulation system, coloured by integration measure (high by red and low by blue); (c) linear circulation system, coloured by connectivity; (d) linear circulation system, coloured by integration; (e) curved circulation system, coloured by connectivity; (f) curved circulation system, coloured by integration.