Evidence-Based Parametric Design: Computationally Generated Spatial Morphologies Satisfying Behavioural-Based Design Constraints

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Abstract

Parametric design is an established method in engineering and architecture facilitating the rapid generation and evaluation of a large number of configurations and shapes of complex physical structures according to *constraints* specified by the designer. However, the emphasis of parametric design systems, particularly in the context of architectural design of large-scale spaces, is on *numerical* aspects (e.g., maximising areas, specifying dimensions of walls) and does not address human-centred design criteria, for example, as developed from behavioural evidence-based studies. This paper aims at providing an evidence-based human-centred approach for defining design constraints for parametric modelling systems. We determine design rules that address wayfinding issues through behavioural multi-modal data analysis of a wayfinding case study in two health-care environments of the Parkland hospital (Dallas). Our rules are related to the environmental factors of visibility and positioning of manifest cues along the navigation route. We implement our rules in FreeCAD, an open-source parametric system.

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1 Introduction

Behavioural-based parametric design systems. Parametric modelling is a popular paradigm in the design industry, particularly in the domains of architecture, engineering, and construction: objects are modelled with parameters, constraints are defined between parameters. By "designing by constraints", the designer is specifying a family of designs that satisfy the given set of constraints, and parametric design tools assist designers by providing adaptability and flexibility in the design procedure [13], and enabling them to explore the resulting *design space* in various ways. Two common parametric system tools are *intelligent sketch* and *evolutionary design.*[1]

[1] In intelligent sketch (also called dynamic geometry), a user is able to modify a design e.g. by clicking and dragging objects in a visual representation of their design, and the system automatically adjusts

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While parametric design systems lend themselves well to the manipulation of numerical, geometric features and relationships between object parameters (typically support points, lines, circles, and incidence and orientation constraints), and they have thus far failed in integrating the dimension of human behaviour as a variable of morphological formulation. Currently, all prominent parametric systems are restricted to constraints that are rather geometric in nature, e.g. maximising a numerical volume, fixing the numerical dimensions of walls, and so on. In [21] we extend industry-standard parametric systems to support a range of qualitative and visuo-locomotive spatial constraints: *incidence* (points interior or exterior to regions), *topology* (i.e. Region Connection Calculus), *size* (smaller, larger), *visibility* and *movement*. In Section 5 we use this extended language to formalise evidence-based design rules.

Evidence-based parametric design for large-scale buildings. Designing for large-scale built-up spaces, the architect needs to take into consideration the visuo-locomotive experience of representative groups of people (e.g. children, seniors, individual with physical disabilities) in various circumstances according to the building's functional program. For instance, designing a health-care environment, the architect sets navigation requirements such as *"the moment the user enters the lobby/corridor of a hospital, they should immediately detect the related signage and be confident to proceed in the correct direction"*. In practice, a user's ability to detect signage varies and the spatial structure of the environment plays a major role (Fig. 1). Consequently, we aim at embedding behavioural evidence into the design procedure and simultaneously support the designer in exploring a wide range of morphological possibilities. These objectives lie at the intersection of evidence-based design and parametric computational design. Our perspective on *evidence-based parametric design systems* is rooted in evidence-based design, and aims to ensure that human-centred design objectives are fulfilled (e.g. people should (not) get lost, the environment should satisfy inclusive design criteria) through a computational generative system. This agenda encompasses research in environmental psychology and cognitive-assistive technologies [21, 18].

2 Behavioural evidence from empirical wayfinding studies

Evidence-Based Design for wayfinding. In this paper we investigate the case of wayfinding experience in large-scale built-up spaces, as an example of using bahavioural evidence from a cognitive process to establish design constraints. Design for successful wayfinding performance in large-scale buildings (e.g. hospitals, airports, museums) includes plan configuration and manifest cues, technology, and user characteristics [10, 14]. The significant variables for wayfinding performance that designers can manipulate include spatial characteristics such as visible lines-of-sight, the position of manifest cues, and the geometry of the layout, colors and lighting, visibility connections etc. [23, 20]. For instance, empirical studies in real and virtual space suggest that people tend to move towards the direction of the stated area with the longest line of sight [25], views to the external environment can enhance the legibility of the interiors [11], and that wayfinding includes both attention to the building structure and to manifest cues (landmarks, signage) [3].

the remaining parts of the design in order to maintain the constraints. In evolutionary design, the system automatically generates designs according to the given constraints, i.e. the designer guides this generative process through constraints.

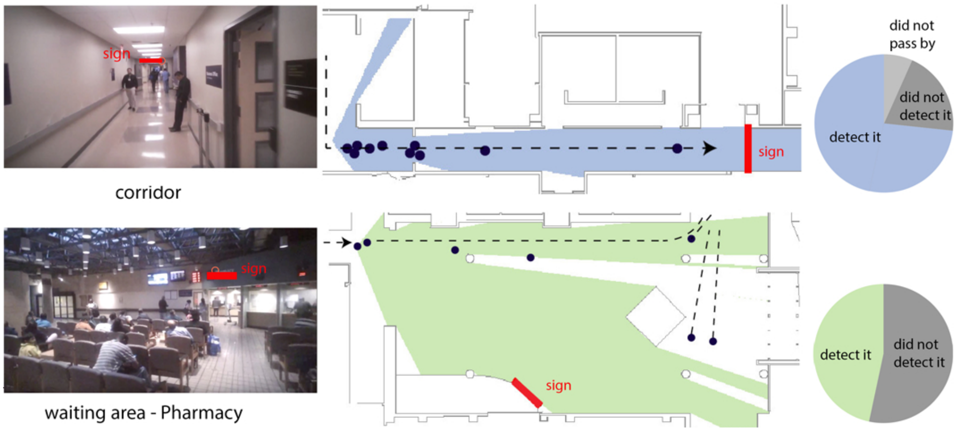


Figure 1 A comparison in behavioural data during wayfinding in a corridor (1.8–2m width) and the pharmacy waiting area (7–8.5m width) in the old Parkland hospital, indicates that the sign above the passage of the corridor was detected by 72% of the participants, while the pharmacy sign (destination point), was detected by 55% of the participants. The isovist analysis reveals visibility differences and justify the behavioural analysis.

Visuo-locomotive experience in a wayfinding case study at the Parkland Hospital. We conducted a wayfinding case study in two health-care environments: the old and the new building of the Parkland hospital in Dallas (Texas). Our study consisted of 25 participants, between 18-83 years old, from the local community that were unfamiliar with the buildings. They were fitted with eye-tracking glasses[2], and were asked to pursue a complex wayfinding task for approximately 15 minutes. With the exception of the vocal instructions given at the beginning of the task, the participants were not allowed to use maps but only the manifest cues (landmarks, signage) which are available in each building. During the experimental procedure we employed a range of sensors for measuring the embodied visuo-locomotive experience of users (mobile eye-tracking, GPS, egocentric and allocentric video recording, questionnaires, manual observations) [7]. Our approach is driven by cognitive vision theory and the high-level semantic analysis of multi-modal perceptual data currently encompassing visual perception analysis, people-movement trajectories based on locomotive path taken by subjects, including other events as well as 3D morphological analysis (e.g., topology, routes, isovists) [8, 17].

3 Integrating empirical and analytical methods to reveal wayfinding issues (I1–I4)

Behavioural analysis of the multi-modal data from our Parkland hospital case study in combination with morphological analysis of the architectural space (a) demonstrates the interaction between users and the Parkland environments, (b) highlights a number of navigation difficulties and uncomfortable situations that participants experienced[3], and (c) reveals environmental features that reduce navigation performance. Many of the outcomes

[2] Wearable eye tracking devices designed to record a person's natural gaze in real-time and capture natural viewing behaviour in real-world environment.

[3] Situations or events that seem to reflect *discomfort* are: time delays, hesitations, detours, or the need to ask for help as well as extensive visual search of the surrounding environment.

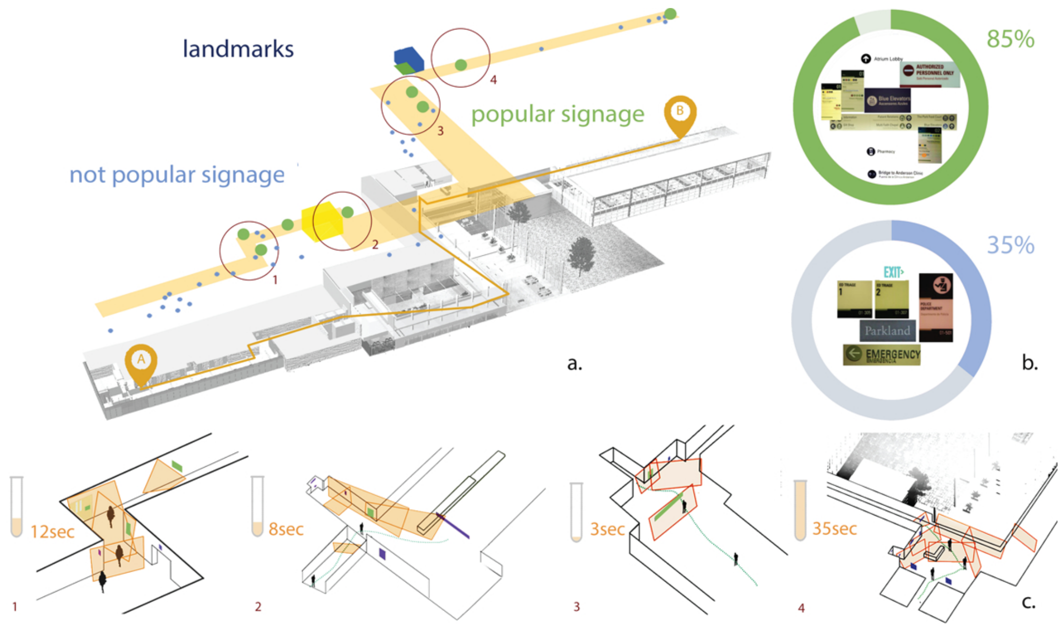


Figure 2 (a) The position of landmarks, manifest cues and decision points along the wayfinding route, (b) signage detection rate, (c) the position of popular (green) and not popular (blue) signage in every decision points and the average time participants spend in each one of them.

confirm prior experimental results about the effect of environmental features on the wayfinding performance concerning, for example, signalization detection, visual connectivity, affordances and manifest cues (landmarks and signage) [24, 2, 12]. In this process, we examine the most, and the least, noticeable signage and landmarks, the time delays at the decision points, gaze patterns in threshold positions[4], visibility connections, the geometry and layout of the scene. Our approach for multi-modal behavioural analysis is founded in Spatial Reasoning, Cognitive Vision and Environmental Psychology [8, 6]. The morphological analysis is based on cognitive design computing foundations resulting in a novel ontology of the *shape of empty space* [5]. As a result, this systematic analysis in the Parkland hospital case study, leads us to highlight four major wayfinding issues (I1–I4).

ISSUE I1 – Signage detection problem at threshold positions. Eye-tracking analysis indicates that out of a total of 60 signs placed along the experimental route in the new Parkland hospital (NPH), only 9 of them have been detected by 85% of the participants, and 6 by less than 35% (Fig. 2b). These results can be interpreted in relation to the morphological analysis of the scene and the layout of the built environment. In particular, the detected signs in NPH, were the ones directly related to the destination and the vocal information given to participants, or they were positioned on decision points vertically along the participant's route (Fig. 2a). Missing signage at a decision point can cause delays, confusion and stress [9]. In the case of NPH, the average time that participants spend at each decision point is directly related to the signage detection rate and the time of the first fixation from the threshold position (Fig. 2c).

[4] Threshold position considers a transitional point between two places in the building, this could signify the entrance to a room of the passage from a corridor to a lobby etc.

To understand how this issue is related to the morphology of the environment and the placing of the signs, we examine the different positions from where participants detect the pharmacy sign while entering the waiting area of the old Parkland hospital, in combination with the line of sight at the moment of detection (Fig. 3a). The distance between the position and the signage varies between 8.7 and 13.5 meters and the viewing angle (formulated by the line of sight and the sign's surface) varies between 10° and 90°. However, the majority of participants detect the sign from an average angle of 78°. Based on DIN-1450 regulations[5] the pharmacy sign (approximately type size 300mm) is readable from 28m distance and visible for an angle between 15° and 90° (Fig. 3b). Even though the distance between the threshold position the sign is less than the suggested by DIN maximum one (15.7 m), the users tent to have difficulty to detect the sign mainly because of the angle formulated between the line of sight of the user in the threshold position and the line representing sign's surface (137°) (Fig. 2a).

ISSUE I2 – Landmarks are not efficient for wayfinding if their position is not related to spatial geometry. The detection of a landmark is based on its position, its size or its differentiation from the environment [16]. Landmarks are important for basic development of spatial knowledge and they enable users to connect fragments of spatial memory in a cognitive map [19]. The results of the behavioural data analysis in the new Parkland hospital indicate that outdoor landmarks in combination with established visual connectivity along the route serve to explain the success of the orientation pointing task that took place after the users changed floors. Additionally, by analysing the visual patterns of participants we observe that they tend to fixate on the outdoor landmarks when these appear in participants' "comfortable" visual range during locomotion. However, in the case of a landmark positioned at a crocked corridor in the old Parkland hospital, 30% of the participants hesitated, slowed their pace, or detoured and asked for help despite the instructions about the landmark in the beginning of the task. These observations show that landmarks are not always helpful in navigation, and that spatial structure must also be considered.

ISSUE I3 – Important manifest cues are not included in the fixation zone of participants. The analysis of participants' gaze directions and fixation patterns reveals a zone of visual search that changes dynamically according to locomotion. In the second decision point of the new Parkland hospital (Fig. 2) the integrated fixation map, for the group of participants, demonstrates that the fixation zone is formulated according to the average comfortable visual range (60° arc) in the moment when participants pass the threshold position (Fig. 4a). As a result, a major signalization text on the right which is not included in the zone was not detected by a large number of participants or it was detected with delay. Additionally, we observe that the zones that map visual attention are changing respectively to the geometric changes of the environment along the route. Specifically, the fixation zones formulated in the corridors of the new Parkland hospital in comparison to the ones from the atrium lobby (Fig. 4b) are narrower in the vertical axis. the comparison between the fixation zones - generated on average by the participants - in two corridors with same dimensions, made of different materials (walls and transparent surfaces) (Fig. 4c) demonstrates a difference on the horizontal axis. As a result, we conclude that the fixation zones created by the participants

[5] DIN (Deutsches Institut für Normung) is the German standards body, and specifically DIN 1450 refers to legibility of texts.

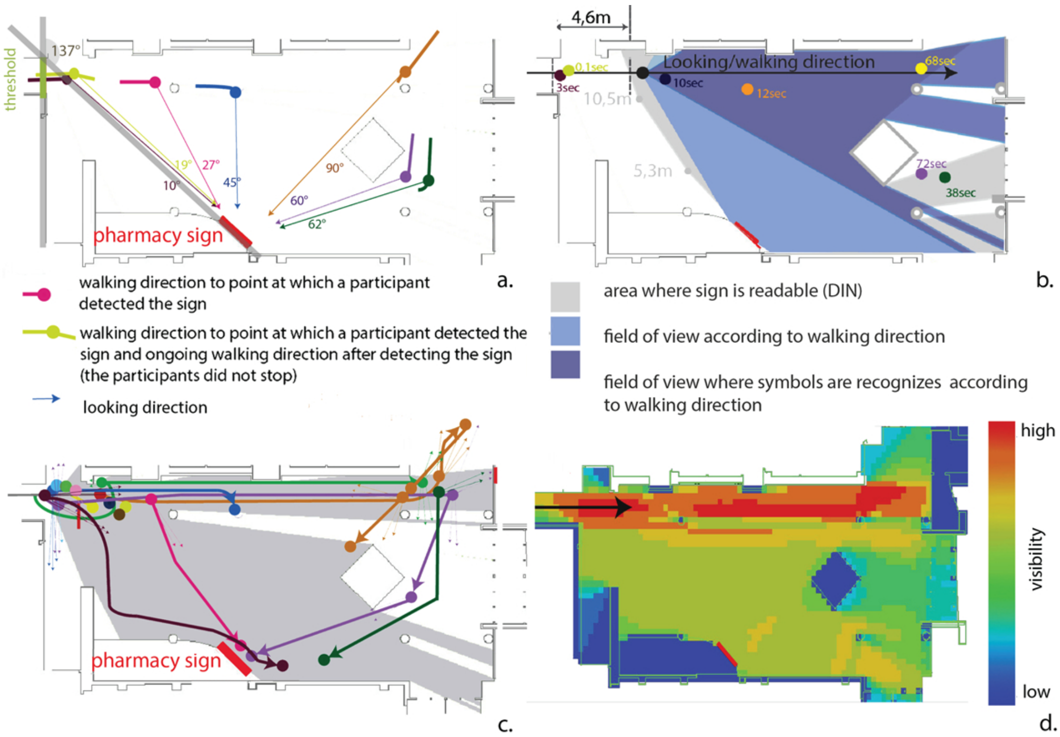


Figure 3 (a) The position of participants, the line of sight and the angle of their view, when they detect the sign, (b) the range of visibility and readability according to DIN regulation in the particular layout and the dimensions of the sign, (c) Isovist graph from the threshold position, (d) Visibility graph from the threshold position.

during the first moments of a visual search are related to the geometry of the space and constitute an important factor for signage and landmarks placement in space.

ISSUE I4 – Participants unconsciously move towards the direction with the longer line of sight. Our observations confirm the argument of Wiener [25] that people tend to move towards the direction with the longer line of sight. In the forth decision point (Fig. 2) of the new Parkland hospital, 70% of the participants did not detect the sign at the threshold position. The eye-tracking analysis shows that participants' visual attention was placed on the open corridor on their right, towards the end of the available field of view (Fig. 5a,c) before they also decide to move towards this direction (Fig. 5b). Moreover, the behavioural analysis for the old Parkland hospital suggests that many people walking on the narrow corridors of the hospital, tend to first observe the farther visual cues immediately after entering a new space, and they also tend to get distracted by several openings along the route (doors, crossroads, windows, glass walls). These outcomes indicate that user's visual attention and decision making could be unconsciously guided by the visual cues under specific circumstances such as distraction or confusion.

4 Evidence-based design rules (R1–R4)

The results of the multi-modal analysis of the wayfinding case study led us to extract some of the major issues that degrade users' navigation performance. Based on these observations

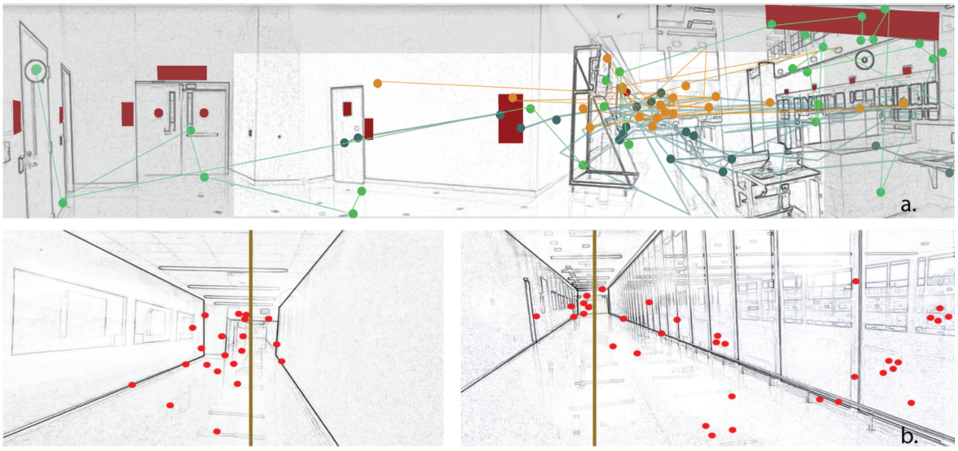


Figure 4 (a)The highlighted zone concentrates the average fixations of the participants from the threshold position at the 2nd decision point in new Parkland hospital. The major sign on the top right is not included in this zone, (b) fixations zones in a corridor and in a corridor with a glass wall and view towards the restaurant of the hospital.

we define design requirements that address navigation issues (I1–I4). We present these requirements in a form of design rules (R1–R4) with the scope to transform them into geometric constraints that can be formulated within parametric design systems.

RULE R1 – The manifest cues should be detected from the threshold positions. The term 'visual field' refers to human's visual abilities concerning the degrees of visual angle during a stable fixation [1, 22]. Humans have an sightly over 180° forward-facing horizontal diameter of their visual field. Their binocular vision covers 114° and concequently the zone where human fixates (fixation is directly related to perception and cognition) [26, 15] is 60° in the horizontal axis and 55° in the vertical axis (Fig. 6a) from which the central 5° represent the normal line of sight each moment. These dimensions create a cone of view, the area where humans are able receive visual information from the surrounding space (Fig. 6b). According to the DIN-1450 concerning signalization text in a public building, the seeing angle[6] is considered different than the viewing angle. The regulations indicate that the legibility depends on the size the signalation text in relation to the distance of viewing and the angle in the horizontal and the vertical axis[7] (Fig. 6c).

As a result, to reassure visibility or readability of a sign, based on humans' visual perception and DIN regulations, the necessary variables to consider are the distance, the viewing angle and the size of the signage. Moreover, based on the behavioural observations, threshold positions are significant for wayfinding. So, the rule (R1) suggests that the manifest cues should be included in the visual range of the user or on the limit of the viewing arc, as this is developed in a threshold position. Considering that this range is defined by the angle of 60° (with central line identical to the route vector), and the radius of this arc is the max distance (based on DIN regulation) so that the size of the particular size is visible.

[6] This is the angle with vertex at the eye and the sides surround the object to see, it is measured in arc minutes ($1' = (\frac{1}{60})°$), minimum for the seeing angle with which the middle length can be perceived: $9'$

[7] The minimum viewing angle with which the middle length can be perceived is 9'.

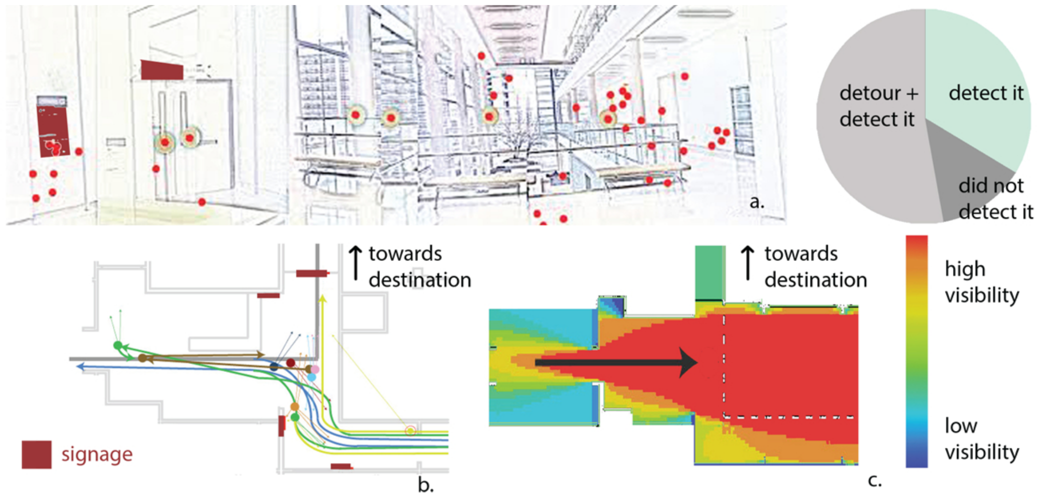


Figure 5 (a) Eye-tracking patterns of participants (on an average level) from the threshold position (decision point 4 in new Parkland hospital (Fig. 2); the route analysis (b) in combination with the visibility analysis (c) confirm that participants tend to move towards the direction with the longer line of sight from the threshold position.

RULE R2 – Ensure visual access to landmarks at the key points of the route where the probability of user's visual fixation is increased. The behavioural analysis of the case study suggests that people tend to detect the manifest cues when they are positioned vertically to the route or within a deviation of 30° towards each direction. As the variable of visual range is dependent on the route line, consequently the dynamic visual field is also shaped according to the limitations of the environmental geometry. This rule suggests that in the design process we should consider possible openings or gaps on the building's volume, based on the intersection between the physical boundaries and the dynamic visual connection between the user with the landmark (Fig. 7). In practice this will provide multiple possibilities that ensure visual connectivity with the landmarks and at the same time it will give the opportunity to the designer to choose the optimal design solution.

RULE R3 – The manifest cues should be positioned such that they are included in the anticipated fixation zone from a threshold position. Eye-tracking data analysis from our case study reveals that the average fixation zone is related to the geometry of the scene as a consequence of the spatial geometry (Fig. 8). Having as an input the three-dimensional space and the route, we are able to estimate the dimensions of the fixation zone, based on the geometrical characteristics and the user's position. For instance, from a threshold position, we draw lines towards the edges of the space that demarcate the horizontal lines of the floor and the ceiling, based on the egocentric perspective of the user. This provides the height of the fixation zone and its position on the vertical axis. Concerning the horizontal axis, the width of the zone is identical to the borders of the physical space with the exception of transparent boundaries or gaps, where we should consider a second boundary available on the scene or the arc defined by human's visual abilities (60° arc) (Fig. 8a). This fixation zone can be a useful design tool, because it can indirectly indicate where the manifest cues should be placed (in the three-dimensional space) in order to be visible by the user from a particular threshold position.

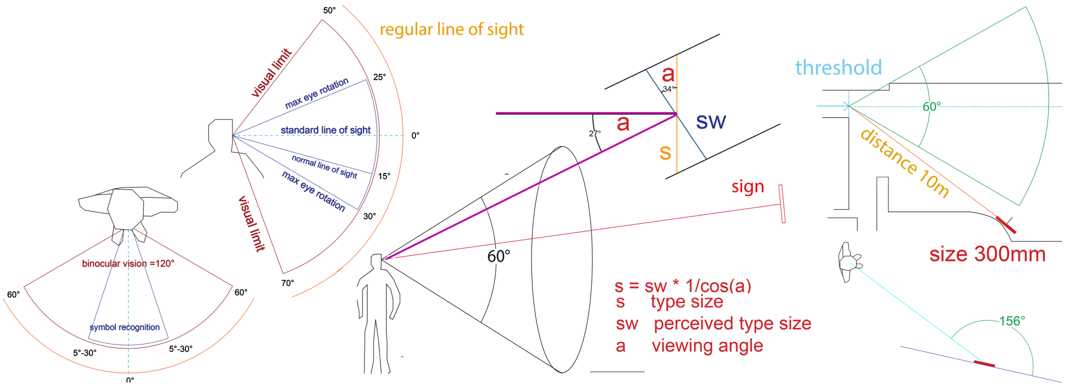


Figure 6 (RULE 1) Taking into consideration human's visual abilities and the design standards for sign legibility, design should ensure that the manifest cues should be detected from the threshold positions.

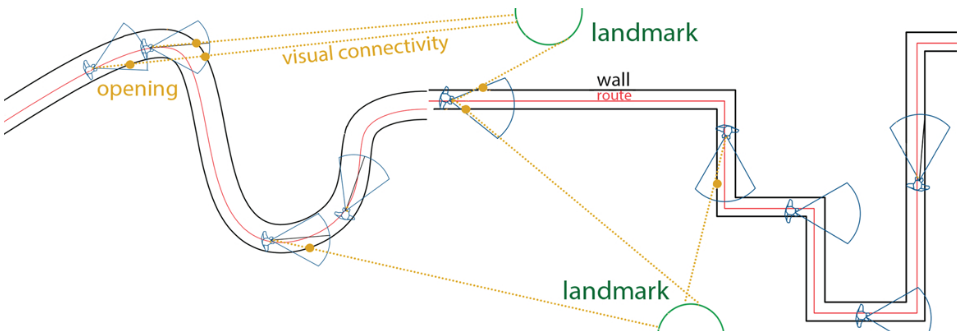


Figure 7 (RULE 2) The design should ensure visual access to landmarks at the key points of the route where the probability of user's visual fixation is increased. The geometry of the building, the available routes together with the dynamic visual range of the user, constitute the necessary variables in the process of defining openings' position.

RULE R4 – The main route provides in every decision point the longer line of sight. Based on our behavioural observations that confirm the results of previous empirical studies, people tend to follow the route that provides the longer line of sight in the decision points. To address the problem of people's disorientation, and detour during wayfinding, we suggest an adaptive system that prioritises the main against the secondary route and modifies the spatial geometry in every decision point according to this principle. As soon as one route is defined as the main one, this route should follow a new geometric pattern (Fig. 9). We expect that this tool could provide suggestions to the designer concerning the modification of significant decision points in a functional diagram of routes of a large-scale building.[8]

[8] A main route is defined as a path for the general public that visit a large-scale public building. It should be distinguishable from the routes used by the staff, or specialised emergency transfer routes. A main route in a hospital is considered to be a route from the atrium lobby to the restaurant, or in a airport from the entrance to the main boarding gates. In large scale public buildings, where multiple paths are involved, defining one route as "main", depends on the critical opinion of the designer.

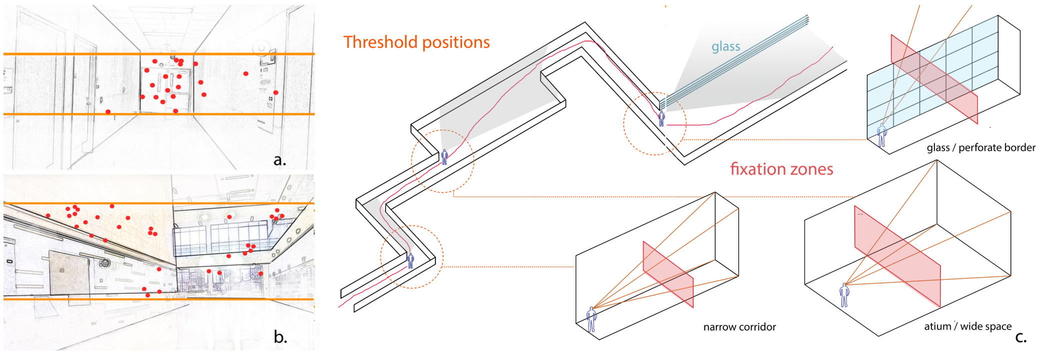


Figure 8 (RULE 3) (a–b) The dimensions of the fixation zones depend on the geometrical characteristics and the materials of the built environment, the height of the zone in a corridor and an atrium lobby differs significantly; (c) The manifest cues should be positioned such that they are included to the anticipated fixation zone from a threshold position.

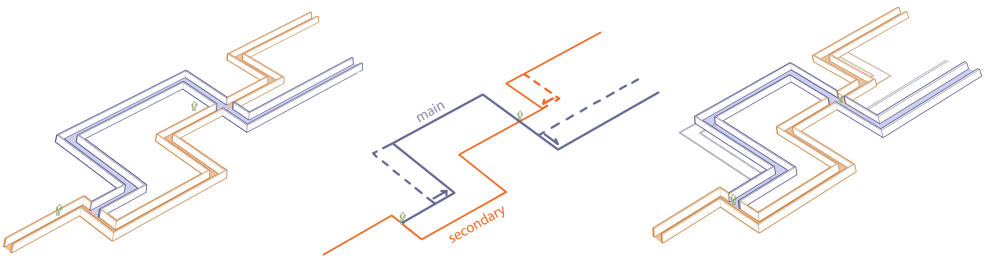


Figure 9 (RULE 4) If you define one of the route as the main, then the geometry of the space can be adjusted so that a user will experience longer view towards the main route in several decision points during his path.

5 Translating design rules to parametric design constraints

We now use our extended parametric constraint language [21] to define constraints that express evidence-based Rules R1–R4. We have implemented all rules in the constraint system FreeCAD. A two-dimensional point $p_i = (x_i, y_i)$ is defined by two real coordinates x_i, y_i. A two-dimensional line from point p_i to point p_j is denoted $[p_i, p_j]$. A vector from point p_i to p_j is $(p_j - p_i)$. An oriented point $o = (p, v)$ is a point p and a vector v. A $\mathsf{triangle}(p_1, p_2, p_3)$ is a polygonal region defined by points (vertices) p_1, p_2, p_3. Let $\theta(v_1, v_2)$ be the angle between the vectors v_1, v_2. Let $d(p_i, p_j)$ be the distance between points p_i, p_j. All distance units are in *metres*.

RULE R1: This rule requires that a sign (represented by oriented point $o_2 = (p_2, v_2)$) be placed within a certain distance and angle of a viewer ($o_1 = (p_1, v_1)$). Let p_1 be the point from which a sign must be visible (e.g. the entry point of a room), and let v_1 be a vector representing the facing direction from which the sign must be viewable. Let p_2 be the location of the sign, and let vector v_2 be the orientation of the sign (i.e. the direction that the sign is "facing").

Constraint: $\mathsf{visible\_sign}(o_1, o_2) \equiv_{\text{DEF}}$

$$\begin{aligned}
\theta(v_1, (p_2 - p_1)) &\leq 30°, && \text{(sign location is within user's field of view)}\\
d(p_1, p_2) &\leq 10, && \text{(sign location within viewing distance)}\\
\theta((p_1 - p_2), v_2) &\leq 10°. && \text{(sign must face viewer)}
\end{aligned}$$

RULE R2: This rule restricts the location of a window opening so that a landmark can be viewed from the user path without requiring the user to turn their head beyond 30° along the direction of the path. Let p_L represent the point location of the landmark. Let p_1, p_2 be the start and end points of the user path along a corridor from which the landmark is intended to be visible. We define a point p_V that represents the last point along the path from which p_L is visible from the required viewing angle.

Constraint: $\mathsf{visible\_landmark}(p_L, p_1, p_2) \equiv_{\mathrm{DEF}}$

$$\begin{aligned} \exists p_V, & \qquad \text{(introduce point representing last viewing position)} \\ p_V \in [p_1, p_2], & \qquad \text{(last viewing point lies on user's path)} \\ \theta((p_2 - p_1), (p_L - p_V)) = 30°, & \qquad \text{(last viable line-of-sight is 30°from user's path)} \\ p_W \in \mathsf{triangle}(p_1, p_v, p_L). & \qquad \text{(window lies within viewable region)} \end{aligned}$$

RULE R3: This rule constructs a 3D "viewing" volume that determines where signs should be placed to be noticeable. In the simplest case the viewing volume V is a polyhedron defined by six vertices based on a given oriented point (p_A, v_A) representing the observer. We construct this volume using isovists [4]. A 2D isovist is a polygon defining the set of points visible from a given point (top-down perspective). Let 3D point $p_1 = (x_1, y_1, z_1)$ be defined by horizontal coordinates x, z and vertical axis y. Consider Figure 11 with the viewing polyhedron V defined be vertices $p_1, \ldots, p_6$:

- generate the 2D isovist from a top-down perspective
- rotate v_A 90^o anticlockwise and clockwise (horizontal plane) to construct vectors v_B, v_C
- extend v_B, v_C until they hit the isovist boundary to get $(x_1, z_1), (x_2, z_2)$ (resp.)
- extend v_A to find surface w; select isovist vertices on w to define $(x_3, y_3), \ldots, (x_6, y_6)$
- the vertical position of p_1, p_2 equals the vertical position of p_A: $z_1 = z_2 = z_A$
- the vertical positions of vertices $v_3, \ldots, v_6$ are determined by the base and height of w.

A sign represented by a 3D point must remain within volume V. If the position or direction (p_A, v_A) is modified then V is reconstructed. This procedure for generating volume V also applies in more complex environments where the end surface w consists of more vertices.

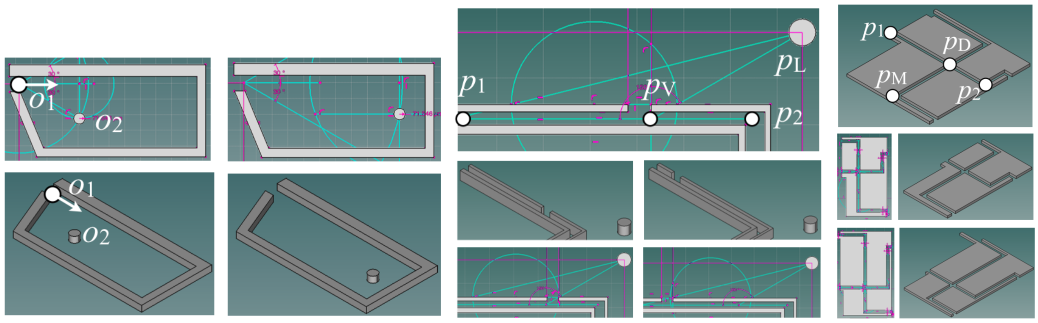
RULE R4: This rule requires that main corridors have a longer line-of-sight from a given decision point than the lower priority corridors. Let point p_D be the decision location where the user will stand, with n corridors to choose from. Let points $p_1, \ldots, p_n$ be the farthest viewable point from p_D down each corridor, i.e. the line $[p_D, p_i]$ is an unobstructed line-of-sight for each $i = 1 \ldots n$. Let M represent the main corridor, $1 \leq M \leq n$. The length of the line-of-sight from p_D to p_M must be longer than all other lines-of-sight from p_D:

Constraint: $\mathsf{priority\_corridor}(p_D, M, p_1, \ldots, p_n) \equiv_{\mathrm{DEF}}$

$$d(p_D, p_M) > d(p_D, p_i), \text{ for } i = 1 \ldots n \wedge i \neq M.$$

6 Summary and Outlook

Parametric design shifts the designer from the position of the *author* to the position of the *coordinator*. The designer defines variables and rules to create and modify a structure through an adaptable and flexible procedure. However, a significant gap exists between the parametric tools, developed for designing human space, and the human experience inside



(a) R1: position of sign o_2 restricted by distance and orientation to viewer o_1.

(b) R2: window to landmark p_L must be within triangle p_1, p_L, p_V.

(c) R4: $[p_D, p_M]$ is longest corridor.

Figure 10 Constraints R1,R2,R4 implemented in the parametric system FreeCAD.

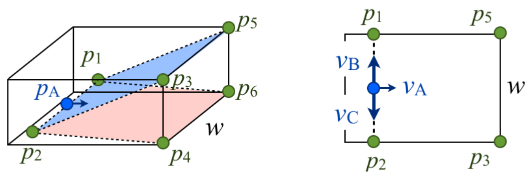


Figure 11 Constraint R3: (left) viewing volume polyhedron (vertices $p_1, \ldots, p_6$) from observer at p_A; (right) defining horizontal coordinates using isovists from a top-down perspective.

the generated design. Everyday human experiences, such as a wayfinding task in a public building, should be directly addressed in such design processes.

We propose to bridge this gap by introducing a human-centred parametric design approach coordinated by evidence of empirical studies. Parametric synthesis seeks the specification of the properties of the elements present in the encountered topology. For this reason to embed people-centred variables into parametric design systems, we establish design constraints based on human embodied visuo-locomotive experience in space. In the case of a cognitive process such as wayfinding, these constraints should be fulfilled with respect to the environmental aspects that influence the wayfinding performance (e.g. visibility, positioning of manifest cues). In this study we present examples of how to define design rules based on behavioural evidence derived by a wayfinding study conducted at the old and the new Parkland hospital in Dallas, and how to translate them into design constraints that can be utilised in parametric design modelling systems.

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