Chapter 9
People-Centered Visuospatial Cognition. Next-Generation Architectural Design Systems and Their Role in Conception, Computing, and Communication

AU1 **Mehul Bhatt and Carl Schultz**

Abstract When undertaking the task of design, architects imagine and anticipate the visuospatial and navigational experience of building users during the initial design conception phase. The ultimate goal is to ensure that the final physical built-up structure inherently performs with respect to people-centered design criteria encompassing function, behavior, and affordance. We argue that next-generation people-centered design systems, frameworks, assistive tools, educational discourse, and design policies and practices need to be explicitly founded on the cognitive modalities of human perception, attention, action, dynamics, environmental affordance and user experience, and design conception and semantics. We posit that this requires a holistic approach to architectural design cognition, encompassing the application of principles, practices, and methods from the fields of architecture and engineering, cognitive science, spatial cognition and computation, and evidence-based empirical methods in environmental and social psychology.

AU2 **Keywords** [redacted]

Architects concerned with designing a building are confronted with *imagining and anticipating* the visuospatial and navigational experience of building users during the initial conception phase. During this phase of design, what architects typically have at hand are high-level client specifications, design requirements, and overall design purposes, as well as *empty space*, i.e., the open site where the project is to be located together with its site-specific context. Architects must envision the *shape of*

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empty space[1] that accomplishes the required economic, social, functional, and aesthetic preferences. Whilst achieving the correspondence between physical structure and function, architects go through a process of creative visuospatial abstraction, design conceptualization, and the translation of an abstract mental model and design specification into a concrete product that can be built in the physical world. In doing so, architects must adopt or anticipate the perspective of a range of possible stakeholders, people groups, and situations, e.g., typical users, everyday scenarios, user experience, users with special needs (blind people, people using wheel-chairs, the elderly, children), and emergency situations.

A key challenge for architects and planners concerned with the design of large-scale public environments is to envision people's interactions, and situation-centered design criteria. From the viewpoint of visuospatial and locomotive perception and cognition within a built environment, architects must imagine a high-level mental model of the design to be built with respect to user experience criteria. The designers' mental models are externalized and refined in a process of iterative design using a range of modalities such as diagrams, sketches, master plans, elaborate computer-aided architecture design (CAAD) models, advanced building simulations, or scaled-down physical replicas for the proposed design. To reiterate, the crucial goal of the abstract design conception and iterative refinement is to ensure that the final product, i.e., a physical built-up structure, inherently performs with respect to people-centered design goals encompassing functional, behavioral, affordance criteria identifiable with respect to the symbiotic relationship between human behavior and the built environment.

The basic proposition of the research presented here is that next-generation people-centered design systems, frameworks, assistive tools, educational discourse, and design policies and practices need to be explicitly founded on the cognitive modalities of human perception, attention, action, dynamics, environmental affordance and user experience, as well as design conception and semantics. The core question that we address and elaborate on is: how can these (people-centered) cognitive modalities explicitly constitute the foundational building blocks at all levels and stages of design education and training, academic design discourse and design studies, and the professional practice of spatial design for architecture? We posit that this requires a holistic approach to architectural design cognition, encompassing the application of principles, practices, and methods from the fields of architecture and engineering, cognitive science, spatial cognition and computation, as well as evidence-based empirical methods in environmental and social psychology. Our proposed holistic approach to architectural design cognition is particularly driven by: designer intention, design form and function, universal access and usability, as well as individual and group well-being in the built environment; in this context, we address research questions pertaining to design conception, design computation, and design communication:

[1] The concept of the *shape of empty space* (Bhatt et al. 2012b) is elaborated on in Sect. 9.2.

– *Conception*: CAAD tools provide robust geometric modeling and structural engineering methods, but how can the future evolution of (architectural) design computing bring notions of design semantics, structure, function, and people-centered design to the fore at an ontological, representational, and computational level?
– *Computation*: What is the role of specialized forms of visuospatial abstraction and commonsense spatial reasoning within the broader realm of design computing, spatial design assistance, and tools for design learning and education?
– *Communication*: What is the nature and form of the analytical feedback that designers and planners expect during the early design conception and iterative refinement phase? What are the implications of this from the viewpoint of the usability, interface, human-computer collaboration and interaction design aspects of architectural design (assistance) systems?

The chapter presents an overview of the core foundational concepts and broad-based research initiatives emanating from our attempts to address the above questions. Section 9.1 presents the concept of "the shape of empty space" as a (prototypical) foundational construct in architectural design thinking, abstraction, and analytical design computing. Section 9.2 presents the human spatial cognition-motivated foundations for what we address as next-generation "cognitive CAAD technology." The emphasis is on modalities of human spatial cognition at the scale of everyday human perception and thinking.

Academic discourse on design studies and design education, in conjunction with system development projects in architecture design cognition and computation, should relate with, build on and, if possible, attempt to seamlessly integrate with state of the art CAAD tools and emerging standards such as Industry Foundation Classes (IFC) and Building Information Modeling (BIM) (Froese et al. 1999; Eastman et al. 2008). This is demonstrated by our work-in-progress prototypical system implementations developed to achieve technological integration with BIM, IFC, and compliant CAAD tools. To show this, Sect. 9.3 presents the visuospatial and locomotion centered "narrativization of anticipated user experience" (in built-up space) as a means to explicitly engage in an analytical dialogue with the architect. The analytical dialog is based on people- and situation-centered objectives encompassing visuospatial cognition, action, and affordance in built-up spaces. We also introduce a prototypical software tool for design analysis and narrativization of cognitive user experience. Section 9.4 presents the manner in which experimental methods in environmental and social psychology and empirically-obtained evidences may be translated into applicable design knowledge and design systems for post-occupancy design analysis (Preiser et al. 1988). We present an evidence-based analysis tool that demonstrates the manner in which knowledge generated from empirically-based methods – such as environmental psychology – may find its way into educational discourse and computational tools for design creation and analysis. Section 9.5 presents a proof-of-concept pertaining to the computational generation of immersive experiences for design prototypes. The focus is on the use of immersive virtual reality and natural interaction technologies to communicate functional design performance from the viewpoint of human behavior simulation. Secondarily, the approach can also be used for the interactive visualization of experimental data (e.g., coming from the kind of evidence-based analysis methods such as in Sect. 9.4). This contribution concludes with a summary of the findings in Sect. 9.6.

9.1 The Shape of Empty Space

Architecture design is about "space": empty space, spatial structures, and the process of structuring. Architects essentially organize empty space by building-up structures and artifacts of people's everyday existence. The process of architectural structuring transforms and organizes empty space into something of a desired form (e.g., a balanced or spacious room, a visually pleasing scene), function (e.g., easily navigable) and semantic connotation (e.g., of a place). Already emphasized, in achieving the correspondence between physical structure and function, architects go through a process of creative visuospatial abstraction, design conceptualization, and the translation of an abstract mental model and design specification into a concrete product that can be built in the physical world. The entire design process, from design conception through engineering and deployment, goes through an iterative refinement cycle consisting of several stages where designers employ the creative and engineering facets of their profession (Akin 2011).

9.1.1 Architecture Design as "Structuring Empty Space"

"Form follows Function" (Sullivan 1896) and "Ornament is Crime" (Loos 1930) have been the cornerstones of the Modernist tradition in engineering design. Within the domain of architectural design, these two doctrines lead to the broad interpretation that the *structural form*, i.e., *shape, layout, connectivity*, of a spatial design (e.g., for built-up space) should be primarily determined by its practical *function* or *purpose*. Much of the literature in the philosophy of design and architecture and the ensuing debates thereof have focused on the semantics of functions with respect to design artifacts and the causal link between form and function. Special emphasis has also been on the question of whether form should, or indeed does, wholly or in part follow function.

The structuring of empty space may be perceived as a process of creative, aesthetic, and functional problem-solving; the empty space itself is a *designed object*, albeit without a material extension in contrast to walls, furniture and so on, where its form emerges from the form of surrounding physical objects, how those objects influence perception and movement, and the activities associated with those objects. As a designed object, doctrines such as "Form follows Function" are applied to guide the creative process. Our operational understanding of structure and function relates to an "iterative refinement by automated design assistance" workflow and is identifiable with respect to the modeling–evaluation–redesign phases in design assistance, for instance, as interpreted within the ontological framework of the Function-Behavior-Structure (FBS) model of the design process (Gero et al. 1999, Umeda and Tomiyama 1997, Umeda et al. 1990). The basic understanding is that a designer or an architect envisions a structure with respect to the designed object's anticipated behaviors (i.e. its properties and attributes) that would satisfy desired functions.

Hence, we have developed a spatial design typology that provides a basis to analyze and "make sense" of the "shape of the empty" that results from a configuration of a designed structure as available within a CAAD model. This is done by establishing a formal link between low-level physical design structure (Fig. 9.1a), and high-level conceptualization of design function (Fig. 9.1b–i) as identifiable by the spatio-linguistic conceptualization of architects, i.e., by modeling and reasoning about design semantics (Bhatt et al. 2012a, b): AU4

Physical Geometry. This corresponds to the physical structure based on the foundational geometric primitives provided by a typical CAAD tool (e.g., wall, door, furniture) (Fig. 9.1a).

Range Spaces. Point-visibility polygons (isovist) restricted to the sensor's angular field of view and focus distance (Fig. 9.1b).

Empty Spaces. Union of movement spaces subtracted by other affordance spaces such as functional and range spaces (Fig. 9.1c).

Operational Spaces. Sweeping, extruding, translating, rotating, and scaling parts of the physical geometry of the reference object (e.g. sweeping a door panel; Fig. 9.1d).

Functional Spaces. Buffer of the physical geometry of the reference object subtracted by obstacles (Fig. 9.1e).

Movement Spaces. Union of navigable surfaces (e.g. slabs) subtracted by obstacles such as walls (Fig. 9.1f).

Route Graph. Connectivity relations between movement spaces and waypoints (e.g. doorways); a movement space is logically connected (i.e. accessible) to a waypoint if they intersect (Fig. 9.1g).

Route Paths. A geometric curve described by precise co-ordinates of motion between a start point and an end point, taking movement obstacles into account such as barriers, furniture, width and height restrictions, slope gradients, and step size (Fig. 9.1h).

Affordance Paths. Particular subsets of route paths that are derived based on specific contexts and situations, such as emergency scenarios (Fig. 9.1i).

9.1.2 Ching's Form, Space, and Order

Architect Francis Ching, in his widely adopted morphological study of problem-solving in (architecture) design, presents a discourse on the core architectural elements of *form*, *space*, and *order*. Ching illustrates the complex interrelations

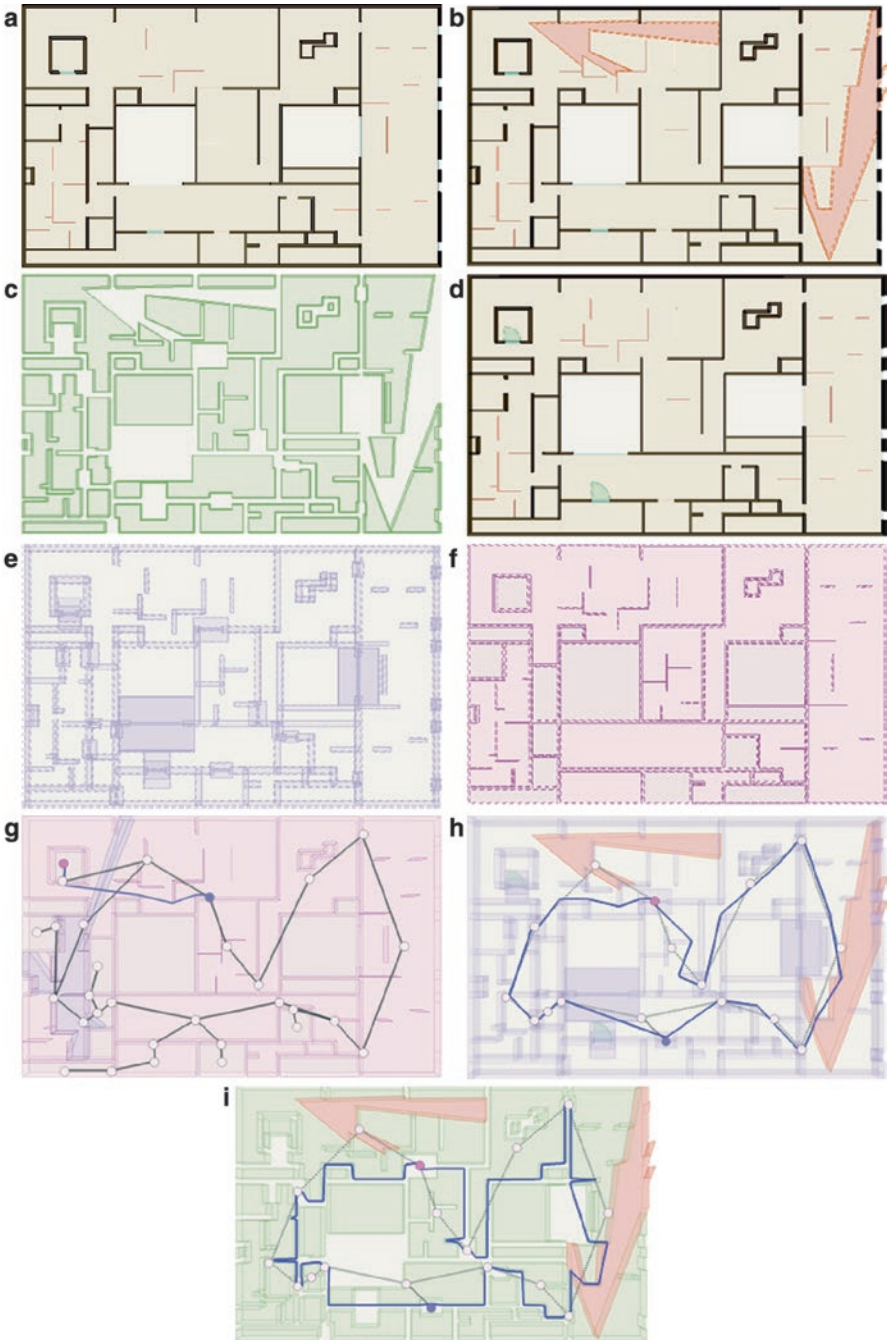

Fig. 9.1 (**a–i**) The shape of empty space: a spatial design typology. (**a**) Physical Geometry in a CAAD Model. (**b**) Range Space (visual, or sensory). (**c**) Empty Space in its strict sense, i.e., as truly non-interfering space. (**d**) Operational Space of doors. (**e**) Functional Space of walls and doors. (**f**) Movement Space. (**g**) Route Graph (logical connection). (**h**) Route Path (with actual path geometry). (**i**) Affordance Path (i.e., with special property of wall-following)

between fundamental design elements, patterns, and constructs occurring within systems of *space organization*, physical structure, and enclosure as they accrue in the design and organization of the built environment. Ching's work constitutes a basic part of many curricula in architecture design and has a clear emphasis on notions of *structure*, *function*, and *purpose*. To quote Ching: "Fundamentally, the physical manifestations of architecture accommodate human activity. However, the arrangement of the elements of form and space will determine how architecture might promote endeavors, elicit responses, and communicate meaning. These elements of form and space are presented, therefore, not as ends in themselves, but as means to solve a problem in response to conditions of function, purpose, and context – that is, architecturally" (Ching 1979: 448).

This is to emphasize the fact that notions of design semantics, structure, and function are mainstream within the theory of architecture design. Furthermore, these, being an essential constituent of an architect's training, are also explicitly known and understood by designers. Yet contemporary architectural design with its computer-aided methods, tools, and paradigms regards the eventual products of design activities as isolated "frozen moments of perfection" – a static view of design without due consideration to the action, dynamics, and interaction of everyday life (Horwitz and Singley 2004: 380).

Human-centered modalities of perception and action do not explicitly constitute the core building-blocks of contemporary design creation, analysis tools and CAAD systems yet. Specifically, even within state-of-the-art CAAD tools, notions of structure, function, behavior and user-centered design are not accessible to the designer. For instance, aspects such as modeling of form and function, simulation of people dynamics, visibility, way-finding, and circulation analyses do not exist within design systems. The paradigmatic foundations of computer-aided architecture design rest on abstractions emanating from points, line-segments and polygons. Contemporary CAAD systems simply lack notions of design semantics, and they do not provide the inherent capability for designers to explicitly apply their learned human-centered notions of design semantics during the professional design process. What is needed is a next-generation CAAD technology that is based on cognitive foundations (see Sect. 9.3).

9.2 Cognitive CAAD Technology

A CAAD system, from a modeling and information theoretical viewpoint, consists of a standard range of geometric constructs involving points, line-segments, polygons, and other complex aggregates of basic geometric primitives. These primitives provide the foundation needed for the structural engineering of the physically built environment using digital means. Recent years have witnessed the development of novel forms of representational and computational paradigms, also inherently geometrically-driven, such as parametric and generative design (modeling and computing). In essence, within state of the art CAAD technology, the design conception, modeling, and design communication (e.g., by 3D visualization) modalities have continued to retain their essential engineering-centered "geometric" character over the years. We argue that this abstract geometric approach to modeling is rather limited, and that CAAD must be augmented by principles of cognition that more directly reflect the way that humans perceive, experience, and act in the built environment.

The *design studio* experience, which is one of the oldest methods for architecture education, learning, and critique, relies principally on design sketches and early drawings, as well as 2D and 3D models at different levels of articulation and detail. The method has evolved and manifests itself beyond architecture schools into the professional realm as well.[2] When one examines the products of design thought during a creative spatial design task (e.g., a studio-based *desk crit* or during the early design conception phase in professional design), the visuospatially driven human-centered nature of the design constructs is evident. Two fundamental modalities, namely visibility and motion, play a fundamental role in design tasks. As an illustration, consider the following spatial design scenarios as they could be phrased in various design tasks:

– *Continuity of perception*. The layout and spatial organization of the reception area of the museum should maintain a sense of "continuity" between locations. Continuity may be thought of as mutual visibility or reachability amongst a set of locations (Fig. 9.2a).
– *Visibility and navigation*. Going from the eastern to the western end of a university campus, certain landmarks should be visible so as to offer a point of reference or localization at all times (Fig. 9.2b).
– *Circulation pattern analysis*. Indoor navigation patterns should be circular (Fig. 9.2c), but it should also be possible to have a hierarchical pattern (Fig. 9.2d) on some days by minimal addition or removal of adjustable partitions or movable walls.

The above examples clearly show the centrality of perceptual modalities. This diagnosis is hardly surprising given that most people primarily experience the environmental space that they are embedded in by a combination of visual and locomotive exploration. Consequently, designers are inclined to project the effects of their design decisions using visuo-locomotive modalities as the principal driving force. This is also reflected very well within the discipline of design research or, more precisely, the research field on human spatial cognition and computation for spatial and architectural design has identified topics such as visibility analysis, way-finding and navigation, spatial reasoning, or indoor spatial awareness as core research strands (Bhatt et al. 2011a, b; Bhattt et al. 2013a). Also, within the theory of

[2] Digital tools and virtual reality based studios have become rather regular in contemporary training methods in architecture design. Goldschmidt refers to this culture where an active engagement with the pencil is being slowly taken-over by digital modeling tools as the era of the "dead pencil" (Goldschmidt 2011). In our human-centered studies, spatial cognition and the visuospatial modalities of design analyses themselves are of principal relevance. The interface, e.g., digital vs. physical, by which the analytical modalities are applied is another issue altogether.

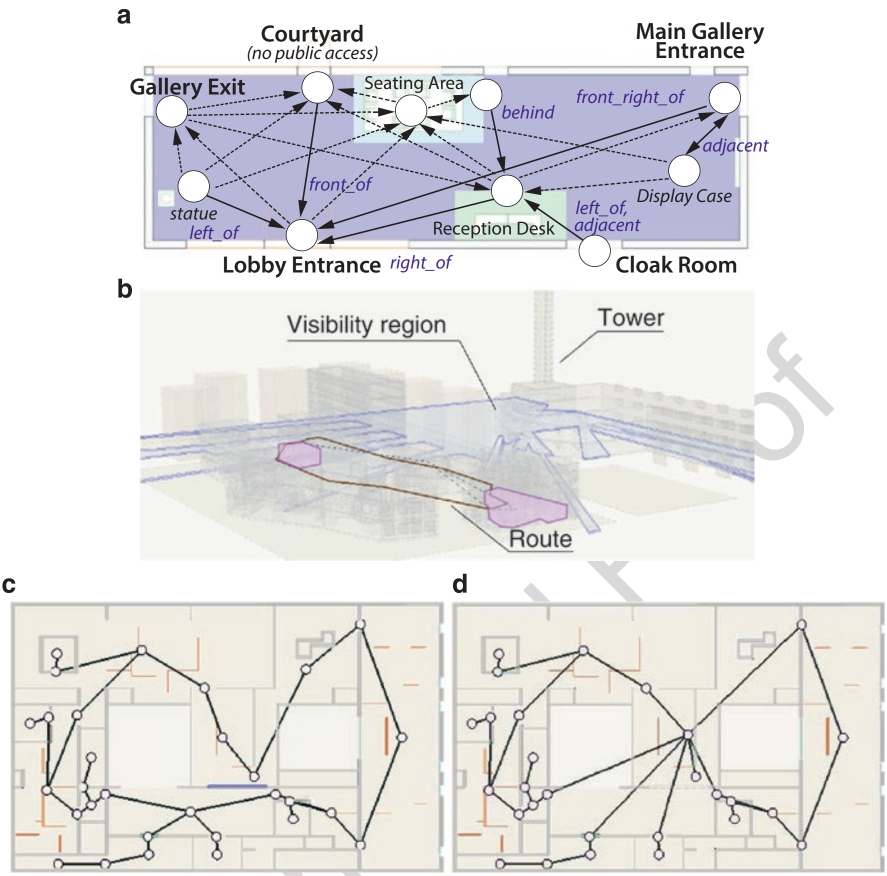

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Fig. 9.2 (**a–d**) Spatial design scenarios with built-up space. (**a**) Museum: continuity as mutual visibility of locations. (**b**) University: Visibility of landmarks for orientation. (**c**) Circular Organization. (**d**) Hierarchical Organization

architecture design, e.g., as approached within a conventional architecture design education, notions of form, space, and order as described in Sect. 9.1 (Ching 1979), and their implications and ramifications from a visuo-locomotive viewpoint are mainstream. Pragmatically, the centrality of visual and motion based analyses is also most directly evident in early design sketches and plans of architects. However, despite the uncontested centrality of this topic, state-of-the-art CAAD tools do not represent and address this important issue.

This is why we propose that the foundational informatics of design systems, tools, and analytical aids concerned with spatial design and engineering tasks should therefore be based on modalities of human spatial cognition at the scale of everyday human perception and thinking (Bhatt et al. 2013b). In particular, design semantics, commonsense spatial cognition, and visuospatial abstraction and computing should be the driving forces underlying the foundations of next-generation design computing systems and paradigms. In what follows we show how this can be achieved with the use of examples from our own research. They address the representation of space from a formal modeling and computational viewpoint, i.e., space, as it is interpreted within the computer science disciplines concerned with the investigation of artificial intelligence and knowledge representation (KR) in general, logic-based geometric and spatial representation and reasoning (Bhatt et al. 2011a, b), as well as spatial computing for design in particular (Bhatt and Freksa 2010).[3]

9.3 Narratives: Linking Architecture, Its Conception, and User Experience

A crucial aspect of the design externalization process is the anticipation of user experience in a building, namely, the experience of individuals and groups that are expected to be the principal stakeholders of the planned architectural design concept. We propose the concept of a *narrative of user experience* as a cognitively founded conceptual framework for visuospatial design computing and cognition (Bhatt et al. 2014). To understand the nature of narratives of user experience from the viewpoint of architecture design, consider the following situation where you are given the task to move around in a building[4]: You enter a building (e.g., a museum or an airport), possibly for the first time; as you walk around, guided by its internal

[3] Although not the focus of this chapter, it is worth mentioning that the emphasis of our research is investigating the in-roads from the artificial intelligence (AI) subfield of knowledge representation (KR) as foundational technologies within next-generation CAAD systems. Our perspective on AI for (architecture) design is founded on the articulation of the Science of Design by Herbert Simon, and with Simon's interpretation of design as a "decision-making process under constraints of physics, logic, and cognition." This view of the scientific design process underlies much of what artificial intelligence has to offer by way of its formal representational and computational apparatus to the domain of design computing. In recent years, several interdisciplinary initiatives comprising of computer scientists, engineers, psychologists, and designers have addressed the application of artificial intelligence techniques for solving problems that accrue at several stages of the design process: design creativity and conceptualization, functionality specification, geometric modeling, structural consistency and code-checking, optimization, collaborative (design) workflow management, and a plethora of other issues. The journal *Artificial Intelligence* for Engineering Design, Analysis and Manufacturing completed two decades of publishing in 2007 and its anniversary publication is a good overview of the area (Brown 2007; Gero 2007).

A sketch of "40 years of design research" is available in Nigan Bayazit (2004). The collected works of the following authors are a rich source of reference and contextualization: Akin 1993; Brown 1993; Chandrasekaran 1990; Gero 1990; Hirtz et al. 2002; Krishnamurti 2006.

[4] A narrative in its most general (dictionary definition) form corresponds to "a spoken or written account of connected events; a story." Narratives serve a crucial role in everyday human perception and cognition; narrativization of everyday perceptions by humans, and the significance of narratives in communication, interaction, and belief formation has been investigated under several frameworks, e.g., discourse analysis and narratology (Herman et al. 2005), the narrative paradigm (Fisher 1987), and through several other interdisciplinary initiatives involving the arts, humanities, and natural sciences. Most recently, the trinity of logic, language, and computer science has begun nurturing the field of "computational models of narratives" (Finlayson et al. 2013; Mani 2012).

structure, you (are required to) form and record your experience based on visuospatial, locomotive, and environmental affordance-based perceptions in the building.

Given the objective to externalize the observed perceptions in the building as required above, a human subject would be able to achieve the task using a range of modalities grounded in language, diagrams, or schematizations, etc. The experience may be described using a range of descriptive modalities such as written or spoken natural language (e.g., involving expressive motion, path, and qualitative spatio-linguistic predicates) (Bhatt et al. 2013b), diagrammatic representations (e.g., sequence graphs, bubble diagrams, schematizations of the environment) or way-finding experience (rotation or turn actions performed, getting lost). For instance, a natural language description of the task introduced above could be as a narrative of user experience as follows:

> As you move in through the passage of the sliding doors, you see a circular lecture hall directly in front through the glass panel, the elevator on the left... Exiting the elevator on level four, there is a door to the left, leading up to a long, narrow corridor with a sequence of offices on the right...

Basically, human cognitive processes concerned with perceptual information processing would be able to externalize a *story*—linguistic or otherwise—that reports the building experience with relative ease; a large-scale experiment—typical in the field of environmental psychology—with many subjects would serve as a good reflection of the collective narrative of user experience in the environment under consideration (Bechtel and Churchman 2002). Architects concerned with designing a building are confronted with imagining and anticipating the perceptual experience of building users during the initial (design) conception phase, at a time when all that exists is empty space. In general, architects must envision the cognitive experiences of a range of people or user groups in different situations (in addition to externalizing their own specialist analyses on functional design performance, and creative and aesthetic preferences).

9.3.1 Computing Narratives of User Experience from Geometric CAAD Models

Our basic proposition is that the foundational informatics of (architecture) design systems, tools, and assistive analytical aids concerned with creative spatial design and engineering tasks should also be based on modalities of visual and spatial cognition at the scale of everyday human perception and thinking; this, we propose, should be driven by processes of perceptual – e.g., visual, spatial, locomotive – narrativization in everyday life.

Descriptions of user experience in buildings, e.g., in the form of a linguistic narrative, may be human-generated, or they could be generated by a system (1) or suite of algorithms (2):

Listing 9.1 depicts an example of the kind of natural language description that a human user may generate. The descriptions are representative of a user experience recording in an existing public building. We refer to these as "narratives of user experience."

Listing 9.1 *Human Generated User Experience* (Gaizauskas et al. 2012): (1) The main entrance to the building is located in a corner under an overhang, which does not allow it to be visible to visitors easily. (2) The immediate interior area around the entrance feels reassuring because it is open and airy. (3) Most of the windows in the consultation rooms overlook the courtyards. (4) [The] space behind the sculpture could be used for outdoor seating in the summer and passers-by would be able to see that there was a cafe available in the area.

Listings 9.2 is an example of computationally generated narratives of user experience descriptions—these have been generated solely on the basis of an elaborate 3D geometric model of the museum (Tostoes et al. 2006) under consideration. We refer to the formal knowledge structures and models (e.g., as represented within a computational system or algorithm) from which such (linguistic or other) descriptions of user experience can be generated as "declarative narratives of user experience." We refer to the process of computationally generating the formally characterized declarative narratives as declarative narrativization.

Listing 9.2 *System Computed Specialist Analysis*: The layout and spatial organization of the museum *maintains "continuity" between locations*. The overall plan follows a *circular structure*, starting at the front lobby, passing through Rooms A, B, C, D, and via the North Door of Room E. The *rooms flow linearly*, and *maintain visibility with the external environment* (except during the segment between Room C and Room D). By *removing* Wall Y in Room X, the *circular ring structure* can be converted to a *hierarchical structure* with Room Z as the central hub. Direct sunlight exposure is achieved in approximately 85% of the floor plan. Region X *never receives any sunlight* at any time during the year.

Our goal is to develop assistive design computing systems that can—based on an underlying formal apparatus—generate narratives of user experience with the descriptive complexity of an architect or a user of a building. As such, they can serve a good developmental benchmark with respect to the performance of a human expert.

9.3.2 TalkingSpaces: *A Prototypical System for Computing Narratives of User Experience*

We present examples of visuospatial and locomotive narratives of user experience that are generated by our prototypical software tool *TalkingSpaces* that implements our proposed Cognitive CAAD approach in design computing.[5] *TalkingSpaces* is a

[5] We emphasize that the analyses and narratives presented in this section have all been computationally generated by a combination of the prototypical software tools developed in our research (Schultz and Bhatt 2011, 2013a, b).

system that generates narratives of visuo-locomotive user experience in built-up space from digital computer-aided architecture design (CAAD) models. The system is based on an underlying declarative narrative representation and computation framework pertaining to conceptual, geometric, and qualitative spatial knowledge derived using the core *DSim*,[6] a prototypic Design Assistance System analysis tool, and the *InSpace3D*[7] middleware. The system integrates seamlessly with industry-scale architecture industry tools (e.g., *Revit*, *ArchiCAD*) and standards (BIM, IFC).

As an example, we consider the case-study in Fig. 9.3a–d) illustrating a floor plan for a proposed academic interchange building at the University of Bremen. The proposed building is meant to serve as a hub of international scientific exchange, hosting research conferences and symposia. In the context of this design, a narrative description pertaining to the following aspects may be derived:

Movement and Overall Layout Structure The initial concept of the organization was centered around a large space or hub from which other spaces and rooms are accessed. A hub organization can be automatically derived by considering the relative room sizes and the movement graph, i.e., information about how distinct rooms and spaces are connected by doorways. A hub layout occurs when one relatively large space is connected to a relatively large number of smaller spaces. Figure 9.4a, b illustrates a visual representation of this analysis, with the following system generated linguistic interpretation: "The design has a hub organization." Each "node" in the movement graph represents either a distinct space, or a place-transition object, namely doorways. A line is drawn between two nodes when there is a direct movement connection between the space and the doorway.

Deriving Paths Through the Main Hub We can now start to simulate and analyze various paths that users may take through the space. Figure 9.5 illustrates a potential user path through the main hub from a variety of entry points. *DSim* determines all unique topological paths between two locations; a topological path is a declarative description of a user path that specifies the sequence of movement spaces and doorways, rather than an actual geometric polyline (illustrated as a dashed grey line between white circles). For each topological path, *DSim* then also simulates various concrete geometric polylines (illustrated as a blue line).

[6] *DSim* is a prototypical Design Assistance System that has been used as a vehicle to demonstrate the potential of next generation people-centered CAAD technology. DSim augments standard 3D BIM by deriving spatial artefacts such as functional, operational, range, sunlight, shadow, and empty spaces. *DSim* provides higher-level design analysis, e.g., with respect to linearity and wayfinding continuity, and automatically derives movement spaces, determines the topological connectivity of designs in a customisable, user-centered manner, and generates concrete geometric user paths through the environment.

[7] *InSpace3D* offers a uniform spatial data access middleware that can provide a combination of high-level, multi-modal, semantic, and quantitative-qualitative spatial data access and analytical capability. It also provides core computational capabilities for the proposed middleware and a high-level spatial model that is compliant with the Industry Foundation Classes (IFC).

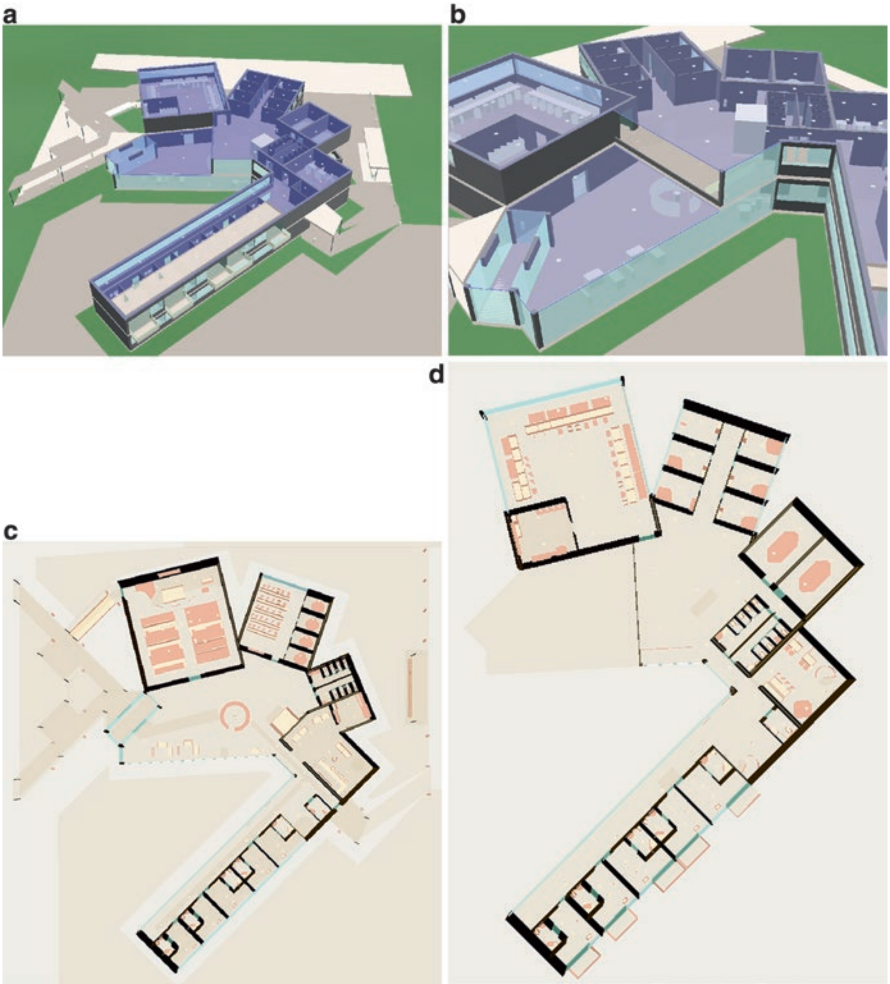

Fig. 9.3 (**a**–**d**) Analysis of the design in full 3D building view (**a**. **b**), and 2D floor plan, ground floor (**c**) and first floor (**d**), view using *DSim*. (**a**, **b**) Analysis of the design in full 3D building view. (**c**) 2D floor plan, ground floor. (**d**) First floor

Visibility Analysis Figure 9.6a illustrates an analysis of the visibility of furniture and other salient objects that can shape the perceived character of a space from a given location along a path: the 360° isovist,[8] standing for the sight of a potential visitor, is represented as a red region. The *TalkingSpaces* system generates the following natural language interpretation: “Moving through the room the visitor can see some windows all around, some doorways all around and some pieces of

[8] An isovist is the volume of space visible from a given point in space, based on a specification of the location of an originationg point. Hence, a 360° isovist indicates the visibility range all around from a given point.

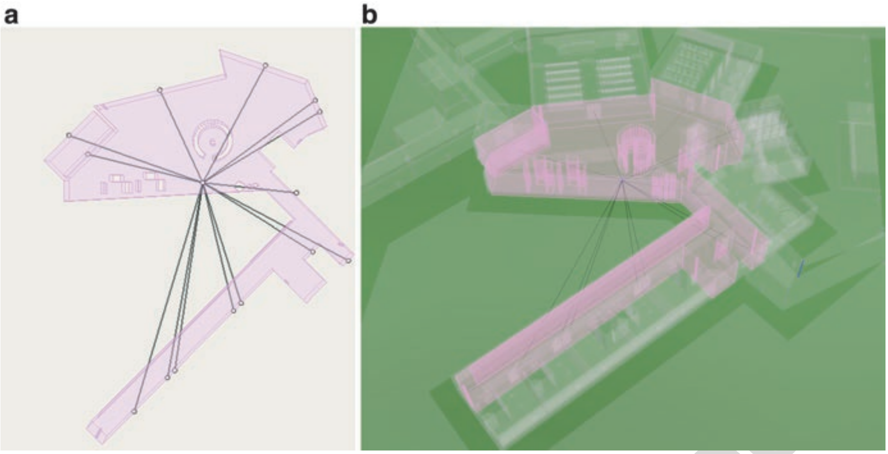

Fig. 9.4 (**a**–**b**) The layout of the design forms a hub structure. (**a**) Plan view of the central hub and connected spaces. (**b**) 3D view of the hub in the building's context

furniture all around." The expression "all around" refers to the orientation of the objects with respect to the location of the user and the direction of their path. Restrictions on the isovist enable distinctions between different regions of the user's visual field. In Fig. 9.6b the direct line of sight is modeled as a more limited region in the direction the user is facing.

Linearity Analysis A sense of linearity can be generally influenced by the number of decisions that persons make as they move through a space. This is evaluated by the properties of empty space, in particular, the number of prominent *holes* in the empty space. As illustrated in Fig. 9.7, the main hub has only one relatively large hole (the reception desk) compared to the size of the space, and so the space is determined to feel fairly linear. The natural language interpretation generated by *TalkingSpaces* is: "The visitor follows the space's fairly linear flow."

Visual Continuity Way-finding orientation and dis-orientation can be analyzed based on the mutual visibility of certain key landmarks and way-finding points through a space; such objects can include signage, unique prominent objects, and entrance and exit doorways. Figure 9.8 (a-b) illustrates the way-finding analysis of the hub as the user moves through the space from one meeting room to another. Dark blue regions indicate mutual visibility and high way-finding continuity where the visibility spaces of the entrance and exit doorways overlap; light blue regions indicate moderate continuity, where only one doorway is visible. The analysis shows that the user has visual contact with both the entrance and exit doorways of each room they pass through for almost their entire path, and thus the space exhibits a sense of orientation and contributes to the feeling of continuity. The corresponding natural language interpretation by *TalkingSpaces* is articulated as follows: "The room is open and continuous."

Fig. 9.5 Plan view of a path from the entrance (*left*), through the main hub (*pink* region), to the restaurant

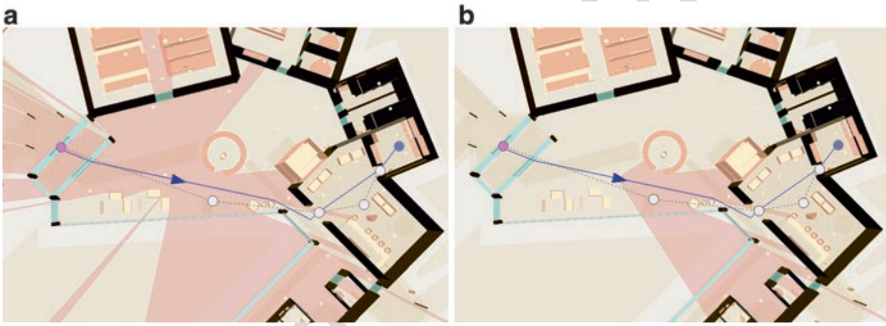

Fig. 9.6 (**a**, **b**) Visible furniture and other salient objects along a path. (**a**) 360° isovist (*red* region). (**b**) Front view of the user (*red* region)

Sunlight Analysis The architect's original concept sketches include a basic sunlight study. The system can model paths of the sun to identify some properties of the design in the context of sunlight and shadow. Figure 9.9 illustrates the analysis of the interaction between sunlight and paths through the main hub. The orange color represents regions of direct sunlight exposure at a given time of day with the position of the sun positioned low on the horizon. In particular, the system is communicating that a large portion of the central hub can receive direct sunlight and other rooms may not receive any direct sunlight. *TalkingSpaces* provides the following natural language interpretation: "Some of the design has direct sunlight exposure."

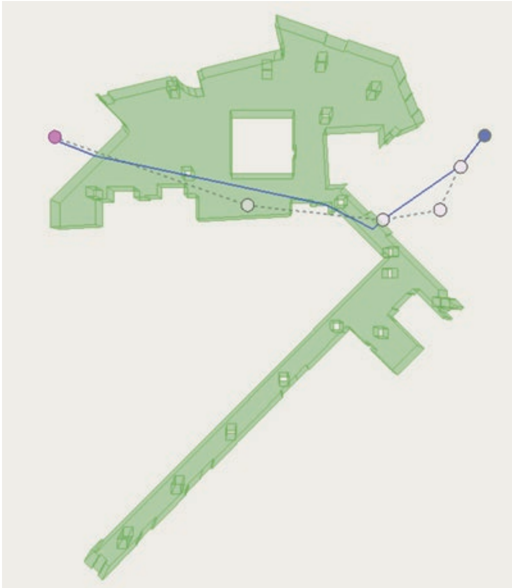

Fig. 9.7 Linearity of the main hub based on the topology of the empty space

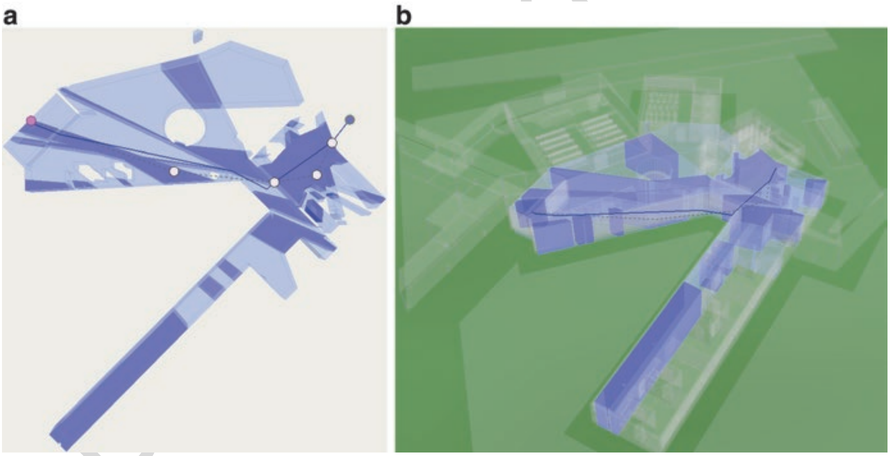

Fig. 9.8 (**a**, **b**) Analysis of way-finding continuity. (**a**) Plan view of way-finding continuity analysis through the main hub. (**b**) 3D view of way-finding continuity in the context of the building

9.4 *MindYourSpace*: A Tool for Evidence Based Design Analysis

A fundamental goal of architectural research is to develop an understanding of the relationship between structural form on one hand, and design performance and user experience on the other. There is enormous potential for technology to assist this figure will be printed in b/w

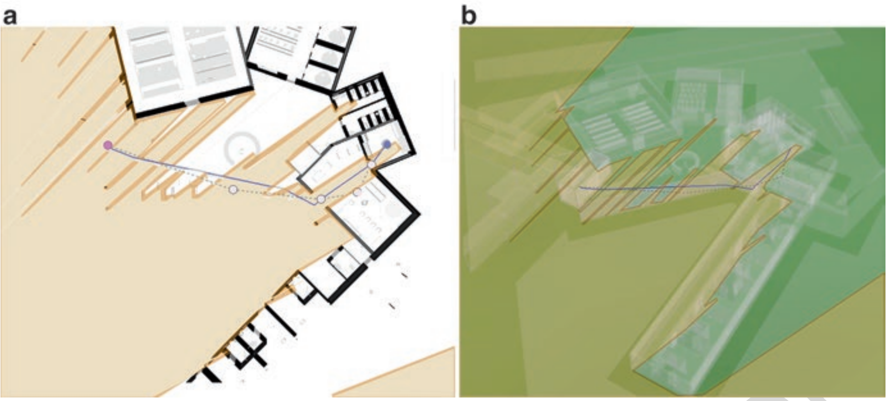

Fig. 9.9 (**a**, **b**) Sunlight analysis. (**a**) Plan view of sunlight in the main hub. (**b**) 3D view of sunlight in the main hub in the context of the building

psychologists and architectural researchers in the acquisition and analysis of data about user behavior. *MindYourSpace* offers the flexibility of conducting user studies within existing, hypothetical, and virtual environments (Schultz et al. 2013, Mastrodonato et al. 2013). It is designed as an assistive tool for the acquisition and high-level semantic analysis of empirical field data pertaining to user experience, visual perception, and navigation behavior in the built environment. The tool aims to support large-scale experiments conducted by environmental psychologists, cognitive scientists, designers, and planners. The underlying foundational aspects of the tool are based on the *InSpace3D* middleware, consisting of a building model that augments standard geometrically-centered models of built-up space (as described in digital CAAD models) with a range of human-centered modalities pertaining to visibility, movement, affordance, and subjective user impressions of space. By this, it provides a technological platform for facilitating field studies, accurately gathering large amounts of information (e.g., timestamps, location coordinates), and automatically performing computational analysis of user behavior data.

A typical architectural research process involving empirical data analysis and knowledge generation consists of three distinct stages:

– *Data collection.* Researchers observe users under specified experiment conditions and record particular features; examples include following users and tracing their paths, interviewing users, "think aloud" methodologies and so on – data collection involves recording navigation patterns, temporal measurements, audio and video streams.
– *Data entry.* Collected data is (often manually) converted into a computer-readable format to enable more rapid analysis, reliable distribution and archiving; examples include entering numerical values into a spreadsheet, "redrawing" pencil-traced paths as polylines in geometry software, and entering interview material into software. This stage is time consuming, tedious, and prone to errors.

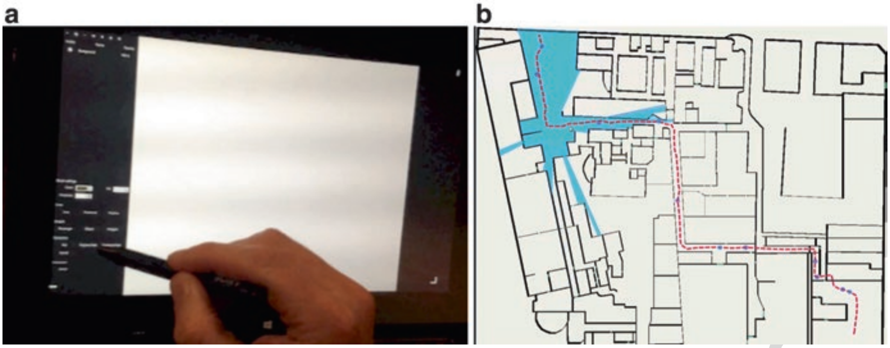

Fig. 9.10 (**a**, **b**) The *MindYourSpace* interface. (**a**) A tablet-based interface. (**b**) Screen-shot of a way-finding experiment

– *Non-semantic analysis*. Researchers "query" their data and search for patterns, features, trends; the absence of a rich, structured model restricts the automatic processing to generic, non-semantic statistical techniques – geometric features such average path length, clustering based on geometric features, and word counts.

Our central aim of employing technology to conduct experiments is to enable researchers to ask certain kinds of semantic, high-level questions about the data they have collected as soon as possible, and to derive *qualitative design knowledge* that may provide a basis for future design projects and policy formation.

9.4.1 Environment, Subjects, and an Experiment

Figure 9.10a shows the tablet-based interface and Fig. 9.10b a screenshot of *MindYourSpace*. In this example, the tool is used to conduct way-finding experiments in the Hospital del Trabajador de Santiago, a trauma hospital in Chile. Red-dashed lines represent the recorded user path, small circles represent points of interest such as "user looked around," and the blue region is the isovist analysis at a given location. The building information model is provided, allowing the experimenter to record paths and points of interest directly in the context of the environment and instantly conduct high-level analysis. In other situations, the experimenter may not have access to a BIM. In these cases, the experimenter can quickly sketch a representation of the environment onsite, and use this to carry out their experiments and preliminary analysis; if any illustrations of floor plans are available onsite (e.g., as a diagram on the wall) then these can be photographed and imported into *MindYourSpace* to be used as a guide for "tracing" over the walls and other salient environmental features. However, crucial 3D information will not be typically available in this case.

9.4.2 User Behavior Analyses and Evidence-Based Design

The ultimate objective of conducting research on user behavior is to feed new information and experiment results back into the architectural design and research communities to inform decision making. Rather than producing large quantities of abstract numerical data, the aim is to generate relevant and easily accessible data in combination with powerful analytical tools.

Using our *MindYourSpace* tool, a designer can access high-level semantic analysis of user behavior with respect to, for example, orientation and visibility. For instance, consider that each recorded path is a single experiment, and possibly hundreds of paths will be collected during the course of an investigation. In *MindYourSpace*, each path is explicitly associated with the context of each experiment, and thus can be used to analyze correlations between particular user groups. *MindYourSpace* may determine that, during a study, people tended to use particular corridors based on the time of day. The experimenter can then ask *MindYourSpace* to identify relevant people-centered properties of each corridor, such as the influence of sunlight. The experimenter can then ask whether any of the properties also exhibit a positive correlation with the data. Certain exceptions to these trends can be studied and accounted for based on the properties of the user groups: blind visitors may not follow the identified trend as the sunlight pattern's appeal is purely visual, busy doctors and other workers perhaps take more efficient paths by relying on their experience of where bottlenecks occur at various times of day, and so on. A plethora of relevant high-level "questions" can be explored using the analytical tools in *MindYourSpace* concerning the following aspects:

Point-of-interest: determining locations where the user behaved in an interesting or revealing way, possibly (although not necessarily) in response to static or dynamic environmental features.

Mental model studies (e.g., rotations): directly comparing and evaluating hypotheses about the user's mental model with empirical results through experimentation.

External visibility and landmark analysis: investigating user behavior in response to visible access to way-finding features in the environment.

Visual drift: investigating the changing centroid of the isovist as the user moves through the environment.

Time information: finding out how ordering of events, relative durations of events, and numerical time records, correlate with user behavioral patterns.

Shadow and light influence: investigating the relationship between user behavior and patterns of light and shadow.

Such features are also analyzed in combination with, for example, locations where people hesitated along *landmark paths*: before having visual access to a landmark, users may exhibit "disoriented" behavior. After an investigation has been concluded, the relationships that the researcher identified between environmental features and user experience are formalized and made accessible in a type of computer-readable online library. Designers can then automatically analyze and evaluate their designs by selecting the appropriate relationships that they are interested in.

9.5 *Immerse3D:* Generating Immersive Experiences

A key goal of developing computational systems and tools driven by the principle of people-centered design is to inform architects about the impact that a design has on user behavior and the elicited subjective impressions. A powerful vehicle for communicating this enormous amount of information to architects is the computational generation of immersive experience.

Based on the early immersive and virtual reality concept, architectural visualization systems place the designers in the role of users through a combination of sensory experiences; this includes immersive walkthroughs and interaction possibilities based on the coupling of technologies and artifacts such as head-mounted displays, 3D projection and sound, precision person tracking, motion capture, and so on (DeFanti et al. 2009). More broadly, technologies such as immersive virtual reality, augmented reality, and gesture-based interaction have a long history. However, they have only recently gained popularity in the field of architectural visualization.

Our prototypical system *Immerse3D* must be seen in this line of development. It presents a proof-of-concept pertaining to the computational generation of immersive walkthroughs based on our people-centered computational narrativization of visuo-locomotive user experience. Conceptualized for a work-in-progress design, *Immerse3D* is technologically based on the foundational capabilities of systems *DSim* and *TalkingSpaces*. The core focus of *Immerse3D* is on the use of immersive virtual reality and natural interaction technologies to communicate functional design performance from the viewpoint of human behavior simulation.

The tool enables the automatic generation of immersive walkthroughs within a full 3D virtual environment of a work-in-progress building design. This is illustrated in the sequence of images from a simulated immersive walkthrough in Fig. 9.11. The focus is on the use of immersive virtual reality and natural interaction technologies to communicate functional design performance from the viewpoint of human behavior simulation. The objectives of the users, and the tasks they undertake, play a role in the generated immersive experience. For example, the architect can simulate the perspective and interactions of a hospital visitor in a wheelchair with the task of navigating from the main entrance to the reception desk (where an interaction with the receptionist can occur), through the various corridors, and finally to their destination room.

Furthermore, *Immerse3D* can be used for the interactive visualization of experimental data that is collected using *MindYourSpace*. The paths and events that were recorded during the experiments can be re-experienced by the architect and other people in an interactive and dynamic manner through virtual reality simulations. The increasing ease of use and affordable availability of such technologies (e.g., the this figure will be printed in b/w

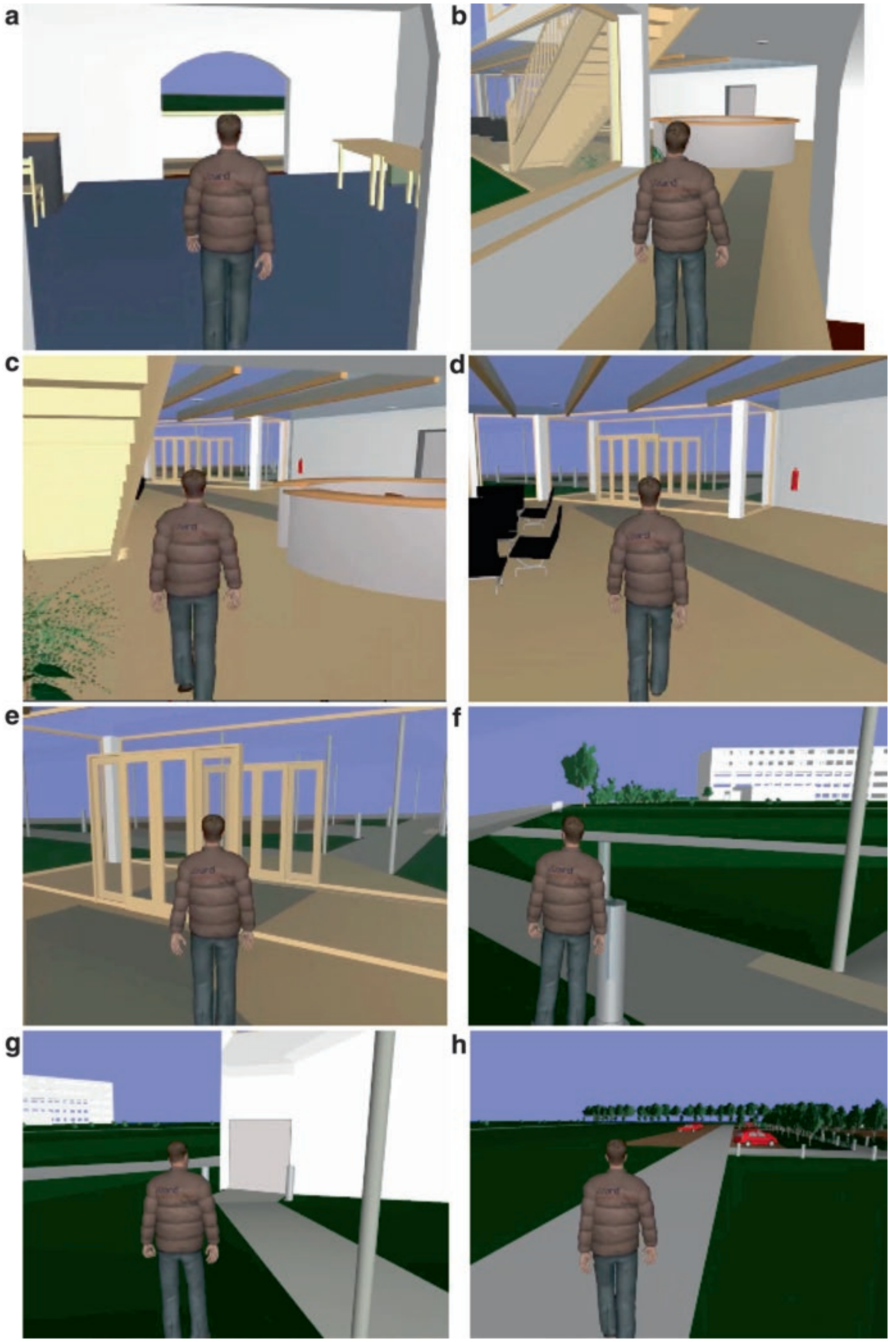

Fig. 9.11 (**a**–**h**) Immersive experience generation

Oculus Rift HMD, providing the sensation of visual depth and a high responsiveness to head movement) means that, in the future, such products could be made available not only to large architectural firms, but also to small design firms, individual practitioners, architecture students, and academics conducting behavioral research at the intersection of psychology and architecture.

9.6 Summary

This is an overview of the research conducted by the DesignSpace Research Group at the Spatial Cognition Research Center (SFB/TR 8), University of Bremen in Germany.[9] DesignSpace Research primarily investigates methods and develops tools for people-centered usability analysis and building performance evaluation at all phases of the architecture design process, encompassing design conception, preliminary prototyping, iterative refinement and (structural) engineering, and evidence-based post-occupancy analysis. Our research focuses on large-scale built environments, and the shaping of *universal design* guided people experiences in them. Research initiatives and their deliverables (i.e., computational tools, empirical findings, case-studies) are particularly concerned with the experience of users from the viewpoint of visuospatial cognition, the functional (design) performance with respect to aspects such as way-finding complexity, and the behavior of the built environment with respect to the dynamic socio-spatial interactions, environmental affordances, and preventable malfunctions in design. DesignSpace Research emphasizes and promotes a *holistic spatial design* creation and an analysis methodology for universal access and usability of the built environment (in the public sphere). It interfaces the state of the art from the fields of architecture design, cognitive science, with a focus on computational cognitive systems, spatial cognition, artificial

[9] Collaborations. The DesignSpace group sincerely acknowledges and is grateful to its scientific collaborators and colleagues for joint initiatives, discussions, interactions, critical feedback, and impulses. Most directly, we thank Robert Amor, Pardis Alizadeh, John Bateman, Jakob Beetz, André Borrmann, Domenico Camarda, Frank Dylla, Gregory Flanagan, Christian Freksa, Gabriela Goldschmidt, Norman Herchen, Christoph Piepka, Joana Hois, Minqian Huang, Franz Kurfess, Oliver Kutz, Giulia Mastrodonato, Frieder Nake, Madhura Thosar, Barbara Tversky, and Rodrigo Vega. We acknowledge the programming support provided by Marc Gerken, Thorben Juilfs, David Koch, Kim Schlingmann, Brian Tietzen, and Daniel Optiz. Software: GRAPHISOFT Deutschland GmbH provided free academic licenses for the *ArchiCAD* design tool – all design and corresponding IFC data used in this paper have been developed / generated using the *ArchiCAD* product. The immersive experience generation capability reported in Sect. 9.6 has been developed on top of the visualization capabilities provided by *WorldViz Vizard 5 Beta 1* software. Funding: We gratefully acknowledge the funding and support of the German Research Foundation (DFG) – the research described in this chapter has been conducted most directly as part of the DFG funded SFB/TR 8 Spatial Cognition Project [DesignSpace], www.design-space.org. We are thankful to Annette Lang and team at the International Office at the University of Bremen for their support of several DesignSpace actions, and in particular toward the International Academic Interchange case-study reported in this chapter.

intelligence driven analytical design computing, and evidence-based analytical methods in environmental and social psychology. This brief overview of our research exemplifies what next-generation architectural design systems could look like, based on sophisticated modeling-tools and a plethora of different image-based interfaces.

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