Navigating Complex Buildings: Cognition, Neuroscience and Architectural Design

Ruth Conroy Dalton
University College London, United Kingdom

Hugo Spiers
University College London, United Kingdom

Christoph Hölscher
University of Freiburg, Germany

This paper is in two sections, the first section presents a review of recent research in the areas of neuroscience, cognitive science and architecture with particular respect to what is currently understood about how building-users find their way around complex buildings. It goes on to define four areas of promising, potential future research located on the boundaries between these three disciplines, these being: spatial knowledge acquisition, orientation, multilevel environments and environment intelligibility. In the second half of the paper, it suggests how such current research and/or any future program of research could be used to aid architects in the design of new buildings. One such method suggested is the creation of design-guidelines or heuristics based upon research into navigation and wayfinding. The paper concludes with an example list of eight sample guidelines.

Introduction

In recent years, an interest has been sparked on the overlap between architecture and neuroscience (in particular, [1], [2], [3] and [4]). The majority of this research appears to focus on either one of two areas: how building users experience architecture and how this may affect them emotionally or, alternatively, on the creative process of architectural design: how it is that architects are able to design buildings and what is happening at the neurological level, during the creative act. In Eberhard's 2009 paper in Neuron, [2], he describes five broad areas that are studied in brain systems science as being: sensation and perception, learning and memory, decision making, emotion and affect and movement or *"how do we interact with our environment and navigate through it?"* (Ibid. p.755). It can be seen that the majority of research hitherto undertaken on the boundaries between neurology and architecture fit into the first and fourth of these areas. This paper, in contrary to these other approaches, firmly concentrates on this latter area of study. To some extents, we are also addressing the second area, namely decision making, but only insofar as it is part of the act of wayfinding and navigation.

This paper will be presented in two sections; the first will examine three distinct and rarely interrelated academic fields, neuroscience, cognitive science and space syntax (a discipline that emerged out of specifically architectural research, but arguably now covers a wider application domain), and will consider what recent developments in each of these fields can tell us about the usability and design of complex buildings, with a strong focus on issues such as wayfinding, navigability and legibility (see Figure 1 for a diagrammatic representation of these three contributions). It will go on to suggest how these different strands of enquiry can be integrated and what potentials exist for future, collaborative research. The second section of this paper will examine the specific implications for the designer by suggesting ways in which these recent developments can be used to assist architects in the process of designing buildings that are more easily navigable and comprehensible, as informed from a spatial, cognitive and neurological standpoint. It is in this last section, that specific design issues will be addressed and we suggest how different approaches or heuristics might emerge from the empirical research in the neuroscience, cognition and architectural communities.

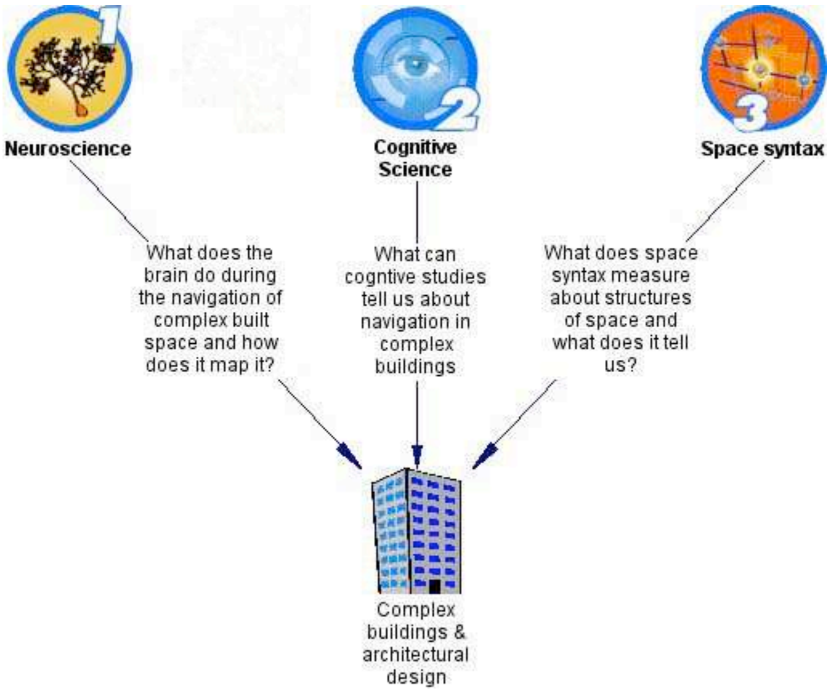

Fig. 1 The relative contributions of neuroscience, cognitive science and space syntax analysis to the design of complex buildings.

What does the brain do during the navigation of complex built space and how does it map it?

If architects are called upon to design spatially complex environments that are effortlessly comprehensible, could it be of assistance to have an idea of what kind of neural activity takes place during navigation or even during the event of simply occupying a space? Until recently, such suppositions would have been purely speculative, but in recent years, through rapid advancements in neural-imaging, it is evident that a diverse network of brain regions are engaged during the navigation of complex built space. Navigation is a multi-faceted cognitive task, which relies on processing sensory information, coordinating movement, remembering the environment and planning. Thus, no wonder so many brain regions are active during navigation. Much has been learned from studies combining virtual reality environments and human neuroimaging. Because neuroimaging requires the participant to remain very still, virtual reality has proved invaluable. Such studies have revealed that a network including the hippocampus, parahippocampus, retrosplenial cortex, posterior parietal cortex and medial prefrontal cortex is more active during navigation [5], [6], [7]. Each of these regions is thought to serve a different purpose. Evidence suggests the hippocampus is responsible for storing an allocentric cognitive map of the environment to guide navigation. The parahippocampus may be important for processing topographical information necessary to determine current location and store information about the perceived environment. Retrosplenial cortex is thought to help translate the allocentric map information into egocentric information, which is processed in posterior parietal cortex to guide bodily movement or imagine movement during planning [8]. The prefrontal cortex is important for planning routes, monitoring possible options and keeping the goal in mind during navigation [9], [10].

A detailed understanding the how the brain supports navigation and maps out the environment has come from studying the neurophysiology of the hippocampal formation. Remarkably, cells in the hippocampal formation appear to contain an internal map and compass to support navigation. Evidence for this has come from recording the neuronal activity while an animal explores an environment. By continually recording the neuronal cell activity in the hippocampus along with the animal's position in an environment and it is possible to map the activity of cells to the surface of the environment and to the momentary orientation of the animal within it. This approach as revealed an elegant system dedicated to spatial mapping and orientation. Due to their distinctive properties cells in different regions of the hippocampal formation have been labeled with names such as "place cells", "head-direction cells", "grid cells", and "border cells". The first to be discovered were place cells by O'Keefe and Dostrovsky in 1971, [11]. These exist in the hippocampus proper and fire action potentials (sending electrical signals to other cells) when an animal is in a particular location in the environment, but are typically silent otherwise. The location in an environment where a cell fires is called its place field. In a given environment only a subset of place cells will be active, with each cell's place field occupying a slightly different location, such that their collective, overlapping place fields carpet the whole environment. Place cells express different activity patterns in different environments, a phenomenon known as remapping. Place cells have several interesting properties. Their response appears to be a high-level multi-modal conjunction of inputs that including information about self motion. They respond predominately to changes in the boundaries, distant landmarks, and large-scale sensory aspects of the environment, such as the floor and wall colours [12]. They can learn over many trials to discriminate very similar environments [13].

Cells in a region next to the hippocampus called the presubiculum also produce a spatially tuned response, but it is not place related. Instead, these cells offer something akin to an internal compass by expressing activity tuned to certain head-directions in the current environment [14] & [15]. Thus, one cell might fire maximally when an animal's head is facing Northeast, another when facing southeast, another Northwest, etc. Collectively the population covers all possible heading orientations. These cells are referred to as "head-direction cells" and have also been found in other brain regions connected to the presubiculum, such as the anterior thalamus and retrosplenial cortex. The cells can be modulated both by vestibular and visual information. When prominent landmarks in an environment are rotated between visits to an environment these cells will tend to follow the rotation, with all cells rotating by the same amount.

"Grid cells" and "Border cells" have both been discovered in the medial entorhinal cortex and subiculum. They are similar to place cells in that they show spatially localised patterns of activity in an environment, but they each differ from place cells in intriguing ways. Grid cell generate multiple place fields arranged in a tessellating grid-like pattern across the environment [16]. If lines are drawn between all fields, their pattern appears somewhat like a sheet of graph paper imposed on the environment, but rather than graph lines being at 90 degree right angles forming squares, the grid lines are at 60 degrees to each other forming triangles. Simultaneously recorded grid cells show the same orientation of their grid pattern within an environment, but may show different spacing between fields. It is thought that grid cells provide inputs to place cells about the distance travelled in the environment. More recently it has been found that the horizontal structure of grid cells is not mimicked in their vertical structure (please see section on multilevel environments for more detail on this), but rather they appear to be stacked in column-like structures.

Border cells [17], also referred to as boundary vector cells [18], are also thought to provide inputs about the environment, and as their name suggests, they signal the location of borders in a given environment. Border cells will typically fire along, or just slightly offset to a border placed in an orientation matching its preferred orientation, e.g. Northwest. An important facet of the system is that in addition to the cells described, conjunctive cells exist, which combine grid or place properties with head-direction tuning (e.g. [19]). These cells will only fire in a given place or set of places and only when an animal is facing in a particular direction. These have been found in the medial entorhinal cortex and presubiculum, but not the hippocampus proper.

What can cognitive studies tell us about navigation in complex buildings?

There are clear similarities and areas of overlap between neuroscience and cognitive science, not least of which is the primary focus of study, namely the human mind. Cognition refers to any of the 'higher-level' brain functions that begin to organize and structure the raw sense data, which represents our 'input' about our surroundings. Spatial cognition research, in particular, is concerned with the acquisition, organization, utilization, and constant revision of knowledge about spatial environments. One way for a lay-person to understand what spatial cognition is about is that it is concerned with how *that stuff out there* (external to us), *gets in here* (is internalized in some manner, but at a far less physical, mechanistic level than would be of concern to the neuroscientist). As in any area of cognitive science, understanding both the underlying cognitive representation formats and the cognitive operations performed on such representations are key issues in spatial cognition. E.g., researchers on 'cognitive mapping' and wayfinding will be interested in both the representational formats of spatial information as well as in the mental operations that translate such information into navigation behaviour or map drawing, but typically not concerned by the actual firing patterns of individual neurons.

Cognitive scientists have often created formal models of wayfinding behaviour that allow larger structures and patterns to emerge. Other cognitive science researchers measure reaction time to investigate information processing. Environment and behaviour researchers have developed tools such as sketch maps, think-aloud protocols, and the tracking of individuals to investigate aspects of human wayfinding such as identifying and creating taxonomies of the different strategies used by people undertaking spatial navigation tasks and investigating the role of individual differences (particular in terms of spatial abilities) in wayfinding performance [20].

So, what contributions have cognitive scientists made to research into the human navigation of complex environments, and what is currently known? First, there is a general consensus that there are three types of spatial knowledge: landmark knowledge, route knowledge and survey knowledge. Landmark knowledge is the identification and recollection of individual, distinct objects located in, and hence inextricably associated with a specific point in space. One way of viewing this is as a mental coupling between object and location (although the range of objects that can serve as landmarks is diverse, see below for further elaboration). In contrast, route knowledge concerns the storage and recollection of sequences of locations, each location being immediately and directly accessible from the previous location as well as to the subsequent one, such that they form a linked 'chain of associated locations'. Such sequences of adjacent places may be augmented by either directional and/or distance information. Finally, survey knowledge represents the most sophisticated form of spatial knowledge, since it concerns not only individual locations and their relative spatial interconnections, but must include additional information such as relative orientations of points in space and metric distances between places. It is this form of representation that is the most map-like of all the hypothesized forms of spatial knowledge. This progression, from least to most complex (landmark to route to survey knowledge) is also the order in which spatial knowledge is thought to be acquired; survey knowledge representing the ultimate state of greatest familiarity with an environment and hence requiring the longest duration of attainment.

If we move from the more overarching framework of types of spatial knowledge presented above to research into the role of specific factors in people's understanding of their environment, then a number of distinct contributions to the field can be identified, which, when taken together form a coherent picture of how human spatial knowledge is attained, stored and subsequently used. For example, there is evidence that landmarks do appear play a role during navigation, although these are less generalizable or universally applicable (i.e. there is less of a 'one size fits all' explanation) than might have previously been theorized: salience of landmarks, individual differences and the particular form of wayfinding task all appear to play a role in people's selection, use and recall of landmarks [21], [22]. User's internal representations of environments, or cognitive maps, also tend to serve to simplify the external world and hence reduce its overall complexity. For example, slight deviations in routes or paths can frequently be recalled as being 'straighter' than they are in reality, with even some turns being omitted entirely. Routes will fewer turns are perceived of or recalled as being metrically shorted than those containing more changes in direction [23], [24]. Slight misalignments of spatial elements, for example rooms or corridors, are often canonicalized to cardinal angles. For example, an approximate 90° angle may be recalled as being a right-angle and approximate 'grids' can be regularized. In terms of multilevel environments (a large proportion of complex buildings will consist of more than one storey), Hölscher et al. [20] discovered an overriding assumption that subsequent floors will tend to resemble preceding floors, in terms of spatial layout and general spatial structure. When such assumptions are defeated, the resultant effect of wayfinding performance is measurable.

What does space syntax measure about structures of space and what does it tell us?

Space syntax is a set of theories, techniques and methods developed at UCL, London, in the 1970s which sought to describe the relationship between patterns of behaviour and consequent, emergent social phenomena with objective, measurable properties of spatial systems. Unlike both neuroscience and cognitive science, space syntax research originated with questions about the nature of society rather than individuals, which, initially were of scant concern. Let us, therefore, start with society as a whole. One of the fundamental aspects of space syntax research has been the circular relationship between society and the types of spaces that they produce, namely that by studying the spaces produced by a society, we must surely be able to understand something about that society as a whole since spatial structures capture aspects of that society such as its values, power-relations, means of control and societal-hierarchies such as kinship structures. However, in turn, a society inhabits and is instantiated through those very same structures of space, which, in turn, have a direct effect upon all interpersonal interactions. In summary, society shapes space, which further shapes peoples lives-as-lived.

With respect to this paper, however, perhaps we can begin to examine this relationship between society and its spaces of production a little differently. If we accept that humans, for the most part, create the spaces, which we inhabit, these spaces are, unequivocally, artifacts of human creation. Can it not be conjectured that if people conceptualize space in a certain manner, then these underlying spatial frameworks must somehow be encapsulated in the spatial systems we produce and inhabit, and, if so, they should equally be amenable to analysis? If a large enough sample of spatial systems (rooms, buildings, neighborhoods or cities) can be analyzed in such an objective manner that any underlying spatial commonalities can be clearly identified then such universalities might also be able to tell us something about how people conceptualize space. However, how do any such commonalities arise, given that the built environment is the product of so many minds and not simply the product of a single intelligence? This can be explained by Hillier's work on 'description retrieval'. He states, '*…It is proposed that there is [a general mechanism governing the link between geometric intuitions and spatial laws], and that it depends on the proposition that our mental interaction with the spatial world engages abstract relational ideas as well as concrete elements." In general, spatial relations are ideas with we think with rather than of.'* [25]. He uses the term 'description retrieval' to describe the emergent process of building cities in a piecemeal fashion, the process being one of first understanding or grasping the spatial rules of what is already there in order to add to and so reproduce those same spatial rules. It is a ’bottom-up’ process that serves to maintain or even reinforce ‘top-down’ spatial rules. Given that such regularities or spatial commonalities can be observed, even across cultures, it is safe to assume that some process akin to Hillier’s description retrieval must take place.

The other way of addressing the question posed in this section, '*What does space syntax measure about structures of space and what does it tell us?'* is to consider not merely the structures of space, but the ways in which people behave in those spaces, and whether the two are related. In order to understand the cyclical relationship between society and space, early space syntax researchers set out to observe and record aggregate patterns of spatial behaviour such as occupancy and movement. It became rapidly evident that there was a strong and quantifiable relationship between aggregate flows of people through specific spaces and measures of how strategic that space was within the larger spatial system. In essence, the more 'integrated' the space (on average, how accessible a space is from all other spaces, measured mathematically) the more people are likely to pass through it. This strong relationship between space and movement (particularly pedestrian movement, but to a lesser extent, vehicular movement), has become a keystone of space syntax research, as its predictive power to estimate degrees of user flow- and occupancy-rates has become an invaluable tool for architects and urban designers wishing to evaluate schemes whilst still at a design stage. Naturally, such a wealth of observational data on aggregate pedestrian movement also has the potential to make a contribution to our understanding of how people cognize spatial systems.

Two additional areas of space syntax research that may contribute to research on human spatial cognition are 'angularity' and on 'intelligibility'. Angularity essentially represents a refinement of the basic space syntax analytic methods that considers not merely the topological relationship between two spaces (if two spaces are adjacent such that it is possible to pass unhindered from one to the other without passing through any intervening spaces, then they are considered connected in original space syntax analysis) but rather the physical angle turned through, or the change of direction taken, when passing from one space to another. This change in angle is represented as a set of 'weights' applied to the underlying graph-representation that underpins all space syntax measures. This refinement emerged from empirical work by Conroy Dalton, who observed that routes taken by subjects in a complex virtual environment appeared to favor more 'linear' and less meandering routes [26] and has subsequently been observed in GPS trails of London motorcycle couriers by Turner [27]. Early methodological work on how to re-conceptualize space syntax analytic techniques to include the concept of angular change originated with work by Dalton [28] and Turner [29]. Subsequent work by Hillier and Iida [30] served to quantify the increase in predictive power of the new angle-based analysis by using an observational dataset of pedestrian flow-rates taken from a wide variety of London neighborhoods and then correlating these to three measures of spatial structure: one using topological-based space syntax analysis, the second utilizing angle-weighted spatial graphs and finally a metric-based measure, in which the distance separating two points in space adds additional weights to the graph. When compared to the observational dataset, Hillier and Iida found that the newer angle-based measures produced significantly higher correlations than the original topological measures or even the distance-based measures, which performed least well of the three [30]. Figure 2 shows the plans for the neighborhood of Barnsbury and Figure 3 shows the correlation coefficients for four districts and the shortest path (metric), least angle (angular) and fewest turns (topological) measures.

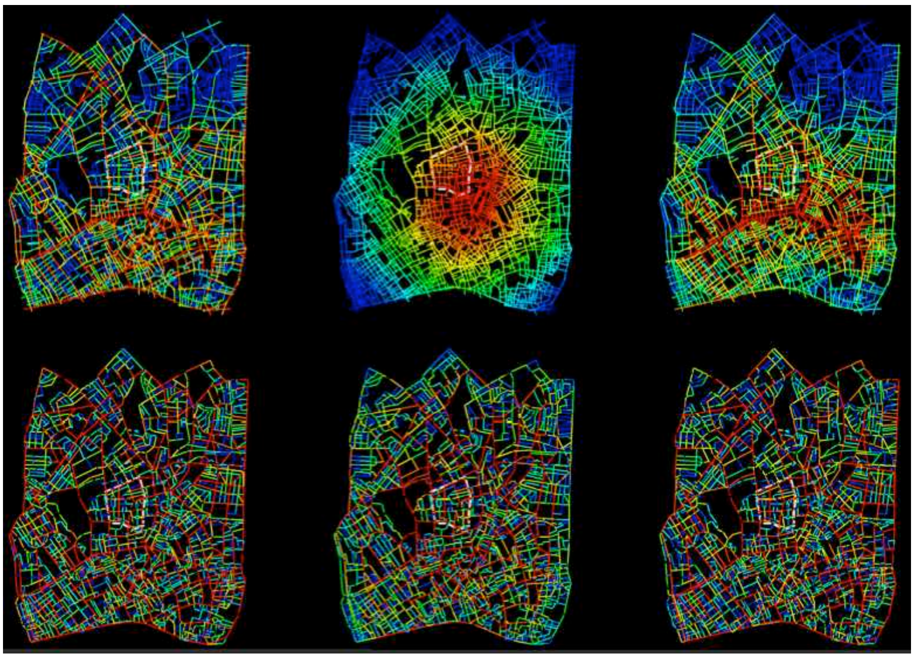

Fig. 2 Angular (left column), metric (middle column) & topological (right column) integration (top row) & choice (bottom row) values for the London neighborhood of Barnsbury (red = high values, blue = low value).

	Gates		Measure	Shortest path	Least angle	Fewest turns
BARNSBURY	117		accessibility choice combined	.169(57) .580 .597	.711(21)* .712* .746c*	.693(12) .572 .700a
CALTHORPE	63		accessibility choice combined	.114(15) .440 .534	.586(39) .552* .615*a	.605*(33) .364 .605a
SOUTH KEN	87		accessibility choice combined	.166(90) .342 .383c	.561*(21) .480 .589(a)	.551(15) .540* .615*a
BROMPTON	90		accessibility choice combined	.124(78) .470 .501c	.626*(66) .528* .644*a	.587 .540 .640a
			mean accessibility mean choice mean combined	.143 .458 .471	.621* .568* .649*	.609 .504 .640

Fig. 3 Pedestrian movement correlation (r2) values for four districts in central London.

Intelligibility is another concept from Hillier [31], that suggests that our ability to find our way around a complex building or environment is partly dependent upon the relationship between local spatial variables and global spatial properties and hence our ability to draw inferences about one from the other. In an intelligible environment, suggests Hillier, spaces that are well connected will also tend to be highly strategic spaces within their larger spatial structure. These connections act as visual cues for the way-finding pedestrian, since they can be easily discerned from the perspective of the situated observer. So, an intelligible environment, is one in which immediate, visual stimuli can provide cues about that which is beyond, and by definition outside, the immediate visual field. In contrast, in an unintelligible environment, the archetypal maze, for example, is one in which local visual cues do not relate to the larger spatial structure or, in the case of a maze, may be deliberately misleading. If this is true, do we actually utilize this spatial relationship to 'read' our environment and make inferences about the spatial structures around us? But, how do we internalize or make use of, consciously or unconsciously, this relationship between local and global patterns of space (the cognitive aspect) and, furthermore, what underpins this behaviour at the neural level?

How might these strands be integrated?

Having described some of the primary contributions of each of the three fields, neuroscience, spatial cognition and space syntax, to current work on pedestrian movement and navigation, this section will attempt to describe areas of synergy between the three approaches and where potentials for interesting interactions or future collaborations lie. First, however, we can immediately identify a problem created by the changes in the scale of focus, between these three academic fields. It can be seen from Figure 4 that space syntax focuses on arguably the largest scale of all (society as a whole) and this change in scale continues until we reach the domain of neuroscience, which can focus on something as small as the firing of a single neuron.

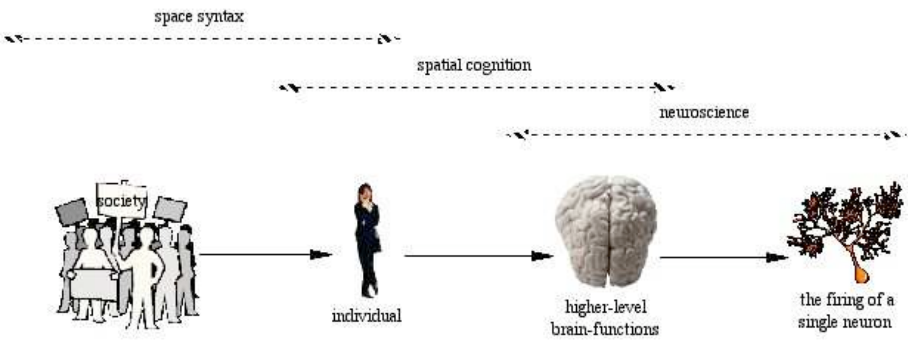

Fig. 4 The research divide between society (as a collection of individuals), the individual, higher-level brain-functions & frameworks of knowledge, interactions between aggregations of neurons and different parts of the brain and the firing of a single neuron.

So, how do we accommodate a shift from a preoccupation with society to the individual and then once more to the single neuron, and is the gulf that is required to be bridged between society and the individual greater or lesser than that between an individual's cognitive framework and their neural activity? One answer, to how to bridge such gulfs in scale, is to instigate collaborations on specific areas of research that initially appear to have the potential to make interesting contributions across two or more fields; areas where there already appear to be some connections or mutual relevance, however tenuous. We would like to initially suggest four areas, namely spatial knowledge acquisition, the role of orientation in wayfinding, multi-level environments (the third dimension) and navigation and intelligibility. The current connections are briefly described in the following sub-sections.

Spatial knowledge acquisition

In the section on 'What can cognitive studies tell us about navigation in complex buildings?', the three different types of spatial knowledge were described as being landmark knowledge, route knowledge and survey knowledge and it is further hypothesized, in psychology and cognitive science, that spatial knowledge is, broadly speaking, acquired in this order. It is suggested in this paper that there are interesting parallels between this sequence of knowledge acquisition and two other establish sequences: first the order in which space syntax measures correlate with observed pedestrian movement flows (angular measures correlating best, followed by topological distance and finally metric distance performing least well of all and second, work that O'Keefe and Caccuci have recently completed [32] into the developmental stage of infant rats, on the relative maturation times of the different cells types, namely head direction cells maturing first, followed by place cells and finally grid cells. And, while it is not being suggested that a direct mapping can be drawn between, for example, research into the firing of head direction cells, angular distance and landmark knowledge (the top row in Figure 5), it is being suggested that there might be some interesting research questions that emerge from placing these sequences in juxtaposition to one another. Is there a relationship between the how we acquire knowledge about environments and the order of maturation of cells involved in spatial orientation, for example, and between either of these sequences and observed aggregative movement rates in cities?

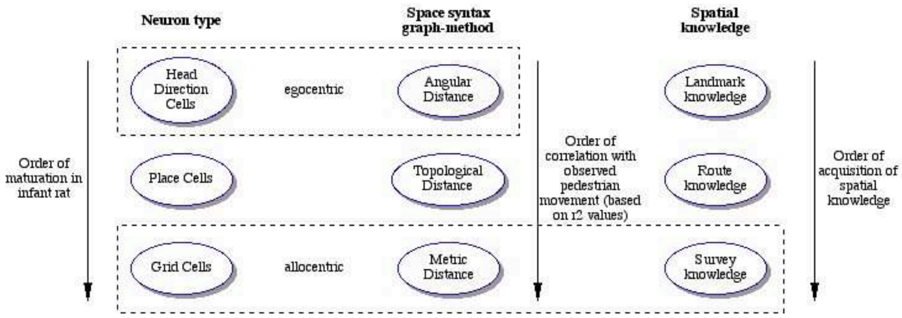

Fig. 5 Left, the order (from top to bottom) of maturation of cells in the infant rat; middle, the order (from top to bottom) of highest correlation with observed pedestrian movement; right, the order (from top to bottom) of acquisition of spatial knowledge. An indication is also given of which of these are fundamentally allocentric concepts and which are egocentric; those omitted have elements of both.

Orientation

In the section on 'What does the brain do during the navigation of complex built space and how does it map it?', the function of head direction cells was described and it is worth remembering that they are not magnetic-compasses since they do not respond the Earth's magnetic field. Like place cells and grid cells, they function in the dark and appear to be most closely linked to our vestibular system (in other words they are sensitive to head-turning) but there is evidence that our visual system serves to re-align our head direction cells regularly to compensate for natural 'drift'. In terms of investigating overlaps with areas of spatial cognition research, there are clear parallels with the 'route angularity effect' [23], [24] in which routes that contain more or less changes of direction are judged to be shorter. It would be interesting to conduct experiments in carefully controlled virtual environments (containing routes of equal lengths and varying numbers/degrees of turns) in order to examine patterns of head cell firing in conjunction with any route angularity effects elicited. There are also clear areas of connection with Klippel et al.'s work on the canonicalisation of route directions, in particular with references to creating natural language expressions to describe directions or the schematization of map-representations of routes [33]. It would be fascinating to establish whether people's conceptions of a 'right turn' or the instructions to 'veer left' have any neurological basis in the firing patterns of head directions cells under in different environments. There are also clear areas of overlap with research from the space syntax community on angular-based measurements of spatial configuration and their strong predictive power on patterns of aggregate movement. One approach would be to modify the angular weightings currently used in space syntax analysis, such that the graph-weightings are far more aligned to human perceptions of angular change [33] and then determine whether correlations with movement patterns improve. Another approach would be to extend Turner's work on using exosomatic visual agents [34] and attempt to give them not only simulated 'sight', as they currently possess, but also a similar sense of direction, provided by a set of simulated 'head direction cells.'

Multilevel environments

What had remained an open question for some time after the discovery of grid cells was how they 'stacked up', i.e. what would be the effect of vertical movement? Did they also appear to form an equivalent, hexagonal, close-packing grid in the third dimension? This question has recently been solved [35] when it was discovered that rat subjects, exploring a helical environment, produced radically different patterns of firing in the third dimension, i.e. it appears that the hippocampus encodes space differently in vertical and horizontal space. The pattern of grid cell (and also place cell) firing appears to form a columnar-packing in the vertical dimension (see Figure 7). One interpretation of this is, rather than our perception of space being three-dimensional, as such, it could rather be perceived of as being 2.5 dimensional, at best (assuming that grid cells in human brains are sufficiently similar to rat brains). This finding aligns particularly neatly with recent work by Hölscher [20] on the navigation of complex, multistory buildings, where he discovered that subjects tend to assume that different floors, stacked vertically, will more or less resemble each other, and when a building is encountered that radically departs from this model (I.e. Subsequent floors do not resemble lower floors in terms of general layout and arrangement, see Figure 6 for an example of such an environment) then subjects can become rapidly disorientated. The finding that vertical space is encoded differently in the brain also serves to counter an occasional but reoccurring criticism of space syntax methods, namely that such methods are essentially two-dimensional and are therefore unable to sufficiently address the third dimension in buildings. The response has typically been that humans navigate in two dimensions rather than three and Verriotis et al.'s recent work on grid cells appear to substantiate this claim.

However, it is clear that additional work needs to be conducted into multilevel environments from the perspective of all three domains, neuroscience, spatial cognition and space syntax. In Montello's recent paper on the contribution of space syntax to environmental psychology, he raises a number of areas of future research, *"In the future, space syntax will be expanded to include aspects of the third dimension in places, including the effects of vertically extended visual spaces on aesthetics and other responses, and the effects of vertical relationships in multi-level structures on orientation and spatial learning."* [36]. Tackling this problem in a unified way rather than as separate disciplines could best approach this manifesto of research into the effects of verticality.

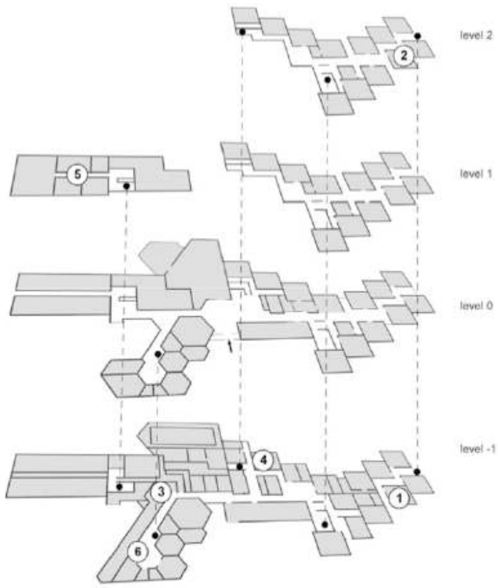

Fig. 6 Stacked, diagrammatic floor plan of the conference centre site used by Hölscher et al. for their study of multi-level wayfinding. Note the disparities between different floors.

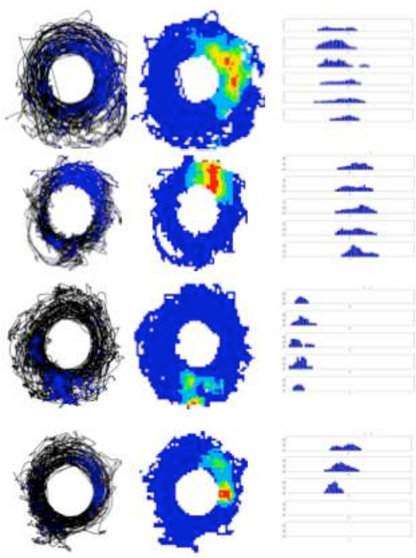

Fig. 7 Paths of a rat's movement through a helical environment (left) and resultant pattern of grid cell firing (right).

Intelligibility

As mentioned in the section entitled 'What does space syntax measure about structures of space and what does it tell us?', intelligibility is a concept from Hillier [37] that suggests that our ability to find our way around a complex building or environment is partly dependent upon the relationship between local spatial variables and global spatial properties and hence our ability to draw inferences about one from the other. Here lies a really interesting epistemological question about whether it is possible to infer global spatial properties from purely local spatial or visual ones and whether the found correlations (in space syntax analyses) between small-scale and large-scale spatial properties are either meaningful or can be actively utilized during navigation. One possible way of linking these different properties would be through a process of Hebbian synapse firing (in which any pair of cells that happen to fire simultaneously will evolve to strengthen their interconnections. In their paper on whether place cells can be connected by Hebbian synapses, Muller and Stead [38] demonstrate how a simulation of a sequence of place cells along a route can form a synaptic chain (through a Hebbian process) and can produce a via route from an origin to a destination, hence making a connection between the local and immediate place and a distal goal location. The Muller and Stead model [38] is a very simple example of how this (inferences about a distal location from purely local information) might be achieved at a neurological level, therefore a similar process (but at a much larger scale of complexity) could begin to account for a process not unlike that of Hillier's 'intelligibility'. However, this would certainly be a learned response and therefore spatial cognitive research into spatial learning and infant development would be crucial to solving the question of how we make judgments about what we cannot see from what we can, as would the contribution of space syntax to incorporate more accurate descriptions of spatial environments into any experimental method.

Implications for architectural design

In this second part of the paper we pose the question: what are the implications for the design of complex buildings, such as airports or hospitals that are regularly castigated as being disorientating and stressful environments? How could such information help an architect to design buildings that are intelligible and easily navigable? As Hillier states [37], architecture is both a rational and an intuitive/creative act and that each aspect is needed to result in a realizable building. If we imagine a future, where many of the questions posed above have been answered, even then would architects be any more able to design buildings that were easy for people to find their way around? The challenge is not merely one of knowing what information might be useful to the designer but also how best it might be made available (In what form and at what stage?). We suggest that the architect could be assisted by being provided with a set of analytic tools, guidelines and design-heuristics (emerging from research into wayfinding and navigation) to support the creative process. This evidence that is currently emerging from the disparate fields of neuroscience, cognitive science and space syntax research, and is already providing a basis for design: evidence-based design. However, this information coming from the different sources needs to be unified and the process accelerated into a clear program of research that aims not only to more fully understand the needs of users of architectural buildings but also to be able to help architects to put themselves into their end-users' shoes (known as perspective taking in psychology), by providing them with appropriate information.

We can begin to provide an idea of how such research could be translated into design-heuristics for architects to act as a checklist for designing for pedestrian movement. (Equally such rules-of-thumb could also be translated into fitness functions for generative designs.) However, the aim of any future program of research, integrating neuroscience, cognitive science and architecture, would be to expand and develop this list:

Design heuristics for architects

1. Straighter, more direct, routes are significantly preferable to routes containing many changes of direction. We recognize in this recommendation a potential conflict between aesthetics and wayfinding requirements: it can be tempting to 'break-up' a long corridor to create 'places' along the route. This may work aesthetically at a local level but will certainly hinder wayfinding [26].

2. Ensure unimpeded lines of sight connecting entrance spaces and other key, central spaces such as atria to the means of vertical circulation: stairs, lifts and escalators. These sight lines are crucial, so it is worth checking these explicitly on plan and/or using software (for example space syntax programs) designed to calculate such lines of sight [39], [40], [31].

3. Where changes of direction/orientation are unavoidable, shallower angles of turning (closer to straight-on) are preferable to sharp turns (and

in particular try to avoid turning angles greater than 90°; forcing a building user to turn back can be disorienting).

4. Wherever possible ensure that differences in layout between floors are not too great. Building users will assume that each floor is laid out in an analogous manner to the preceding floors. Deviating from this too greatly will cause undue confusion [20].

5. When navigating outdoors, invariant visual information such as the horizon, position of sun, slope of ground or distal landmarks such as mountains can provide invaluable orientation checks whilst navigating. In a building, equivalent invariant information can be provided by ensuring frequent and regular sightlines to features such as external views, atria, or visually prominent architectural features.

6. Atria can serve another useful purpose: they can provide a 'short-cut' to survey-knowledge (or top-down and global as opposed to eye-level and local), as they facilitate views to and hence knowledge of other floors that would otherwise be unavailable. This bears some similarity to the concept of 'view enhancing' or the recommendation to climb a tree or another vantage point if lost outdoors [41], [42]. Atria can provide such 'view enhancement' opportunities to building users.

7. Excessive complexity should be avoided. Again, here lies potential for conflict between architectural intent and wayfinding functional requirements. Techniques are available, such as space syntax analyses, to check for overly complex designs.

8. Building users may become lost or disorientated in locations that bear strong visual similarity, at a local level, to other locations in the same building (this can often occur in strongly symmetrical layouts, i.e. one corridor is identical to a neighboring, parallel corridor, [39]). One design technique is to distinguish such locations through non-spatial means, such as prominent use of color. However, relying on internal décor as a navigational cue is problematic as this can unwittingly be altered over the life-time of the building; far better to avoid such spatially self-similar locations at the design-phase. Another method is to deliberately utilize architectural features as 'landmarks'. These work best if placed at decision points and if they are have a large visibility-catchment areas, and so can be seen from multiple locations [21], [22].

Conclusions

This paper constitutes a tentative set of ideas that attempts to draw together research from neuroscience, spatial cognition and architecture (space syntax). This can hopefully serve as a springboard for future collaborative efforts in bringing together these areas but with the clear aim of supporting architects to design more user-friendly buildings.

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