Interdisciplinary approaches for uncovering the impacts of architecture on collective behaviour

Noa Pinter-Wollman[1], Alan Penn[2], Guy Theraulaz[3], and Stephen M. Fiore[4]

1. Department of Ecology and Evolutionary Biology, University of California Los Angeles, Los Angeles, CA, USA
2. The Bartlett Faculty of the Built Environment, University College London, UK
3. Centre de Recherches sur la Cognition Animale, Centre de Biologie Intégrative, CNRS, Université de Toulouse, 31062 Toulouse, France
4. Philosophy Department and the Institute for Simulation & Training, University of Central Florida, Orlando, FL, USA

Abstract

Built structures, such as animal nests or buildings that humans occupy, serve two overarching purposes: shelter and a space where individuals interact. The former has dominated much of the discussion in the literature. But, as the study of collective behavior expands, it is time to elucidate the role of the built environment in shaping collective outcomes. Collective behavior in social animals emerges from interactions, and collective cognition in humans emerges from communication and coordination. These collective actions have vast economic implications in human societies and critical fitness consequences in animal systems. Despite the obvious influence of space on interactions, because spatial proximity is necessary for an interaction to occur, spatial constraints are rarely considered in studies of collective behavior or collective cognition. An interdisciplinary exchange between behavioral ecologists, evolutionary biologists, cognitive scientists, social scientists, architects, and engineers can facilitate a productive exchange of ideas, methods, and theory that could lead us to uncover unifying principles and novel research approaches and questions in studies of animal and human collective behavior. This themed issue aims to formalize and catalyze this interdisciplinary exchange.

1. Introduction

Recently, multiple disciplines have separately begun to study how physical structures influence interactions among individuals and the emergent collective outcomes. For example, research in biology on social insects has begun to examine how nest architecture influences the collective behavior of colonies [1]; research in social and cognitive sciences on humans has begun to investigate how buildings or environmental factors can alter social behavior [2], collaboration [3], and other psychological factors

[4]. Despite conceptual similarities among these fields, that is, theorizing on how the built environment may shape interactions and hence the resulting collective behaviors, there has been little, if any, interdisciplinary communication among these research communities. This themed issue brings these fields together to develop a new form of team science [5] and help shape future interdisciplinary research[1]. By bringing together a wide range of research disciplines and professions – from biology, physics, social science, and architecture – we are better able to pose interdisciplinary questions and identify gaps to create interdisciplinary bridges. These articles illustrate how collaborative problem solving around complex scientific and societal problems can be advanced through teamwork [6]. Further, the methods and theories integrated in this special issue point us towards innovations that can advance our understanding of how to study these forms of complex collaborations (cf. [7]).

The contributions to this themed issue illustrate methodological advances, and implementation of methods to real-world problems through empirical studies and reviews of the literature. In this introduction we first review methodological approaches from biology, physics, and architecture to establish a common corpus of methods that will enable interdisciplinary work on the effects of the built environment on collective behavior, as some of the papers in this special issue have begun to do. We then outline the structure of the themed issue and highlight the findings of the contributed papers. To bring together the methodological approaches and insights from the contributed papers, we offer general research questions for readers to consider. In service of developing an interdisciplinary science of architecture and collective behavior, these questions are developed to prime thinking while readers review the multidisciplinary contributions in this issue.

2. Methodological approaches to study the effects of the built environment on collective behavior

To study the impact of architecture on collective behavior, it is necessary to quantify the built environment and the movement patterns inside these built structures that result in the interactions that underlie the emergence of collective behaviors. Here we outline some of the methods used to obtain and describe these types of spatial and behavioral data and the quantitative approaches that have been used to analyze it.

2.1 Quantifying structures

[1] Some of the manuscripts in this issue emerged from an interdisciplinary workshop on 'The effects of architecture on collective behavior' held in Phoenix, AZ in October 2016.

To determine the impact of the built environment on collective behaviors, one must first quantify the structure of the built environment. This task is not simple because there are many aspects of the environment that might be important to consider. First, physical structures span many scales. The smallest is the 'design scale' which refers to furniture, signs etc. Next is the 'architectural scale' which refers to the arrangement of walls, doors etc. The 'geographic scale' examines the arrangement of buildings, streets etc. [8]. Second, there are multiple features that are part of the structure but are not simply geometric. For example, odors and acoustics can impact the way individuals interact. Social insects relay on the odor of the chambers they occupy to determine what type of task is performed in them [9]. Acoustic signals, such as stridulating, can shape the way social insects move in their nest and structure them [10]. Noise can impact the communication between humans and odors in the environment may prevent or promote the use of certain areas in a building. Thus, an 'odor landscape' or an 'acoustic landscape' may be useful to quantify. For simplicity, we will focus our discussion here on quantifying the geometry and network topology of space. Although this focus on the configuration of space is a simplification, spatial patterns affect the perception of sound, sight and possibly odor, all important modes of communication for social communities.

2.1.1. Extracting spatial attributes

Architects design the built environments that humans occupy, meaning that blue prints and other such representations (e.g., diagrams, sketches), can be used to capture the spatial attributes in the built environment. However, when examining the built structures that animals produce, there is no blue print with which to work. To address this, researchers are required to extract the spatial structure through 'reverse engineering'. The structure of nests that animals excavate can be extracted by pouring into the ground plaster, wax, various metals such as zinc and aluminum [11], concrete, and expanding foam [12]. These materials produce casts of the cavities that animals excavated, which can then be digitized or quantified manually. Another method for extracting the structure of nests is using a CT scanner [13, 14]. The 3D images produced by X-ray tomography allow the accurate measurement of the internal volumes of different structures in the nest, counting the number of chambers, and reconstruction the communication network between chambers. Once the network of a structure has been extracted, the geometry and topology can be described and quantified, as discussed next.

2.1.2. Describing the geometry of space

The geometry of built structures has been quantified with a wide range of methods. Straightforward features such as distances, angles, areas or volumes of rooms and chambers, length of corridors in different locations or depths [12, 15] provide a first glance at the geometry of space. However, these measures do not capture the global structure or the connectivity of the built environment, limiting the kinds of inferences that can be made about global architectural patterns. System-level quantification approaches, such as network theory and Space Syntax provide descriptions of connectivity that go beyond the geometry of a single component, such as a room, in the built environment. Network theory has been used to describe both human- and animal-made structures to quantify connectivity [13], spatial overlap between occupants [2], structural robustness [1, 16], number of junctions [17] etc. In network depiction of structures, corridors or tunnels are usually network edges and rooms or chambers are often the network nodes [1, 2, 17] but sometimes tunnel junctions are represented as network nodes [18, 19]. Once a structure is represented as a network, one can use a wide range of network measures to quantify the structure and its properties [20]. Some of these measures include local connectivity (e.g. centrality of particular nodes or edges [21]), global connectivity (e.g. average degree of all nodes [17]), meshedness (the proportion of cycles in the network [19]), path overlap [2], accessibility (number of nodes in the network that can be reached in exactly h steps from a given node [21]) and others. A powerful method that has been used to quantify and study buildings designed by humans is Space Syntax. This is a theory of human society coupled to a set of methods for representing and quantifying the pattern properties of built space, first developed by Bill Hillier, Julienne Hanson and colleagues [22]. By representing patterns of connected space as networks and quantifying the properties of these networks, it has been possible to control the design variable in comparative studies of buildings and urban areas. Using these methods, it has been established that the configuration of the built environment is a primary determinant of patterns of human movement [23], and the product of these patterns of movement in terms of co-presence in space and communication between people [24]. This special issue brings, to our knowledge the first application of Space Syntax to the study of an animal structure.

2.2 Quantifying movements within structures

To uncover the way in which individuals interact within given structures, their movement and interaction patterns need to be tracked. There are many ways to track the movement patterns of humans and animals. Most commonly, such tracking is conducted through remote sensing either using tracking devices that are attached to the study subjects or with image analysis [25-28]. After movement patterns are extracted, they need to be analyzed to gain insights about the behavior of the individuals in the built environment, for instance their spatial fidelity, identifying the patterns of interactions among individuals and the collective outcomes of these interactions and movements [29].

2.2.1. Extracting movement patterns

Similarly to when quantifying structures, one first needs a description of movements before they can be analyzed. In this case there is more similarity between humans and animals because, in both cases, individuals can be tracked remotely and their movement patterns obtained. Both animals and humans can be tracked using devices that emit radio frequency. Human movements have been tracked by following cell phone signals or radio-frequency-based devices [30, 31]. Similarly, the movement of ants has been tracked using RFID tags [26]. High resolution movement patterns cannot always be achieved using such devices, so, more commonly, the type of information obtained from wearable devises is less granular. Such devices can be used to track interactions directly, through proximity detection in humans [31] and animals [32], and they can record movements in and out of certain spaces, such as stations of public transportation in human movements [8] and the movements of animals in and out of their nests[33, 34]).

Another common way to obtain the movement patterns of both humans and animals is image analysis. Machine vision algorithms have been developed to track humans [35-37], and animals [38-40]. Some of these software can track unique individuals, however, that capacity is usually limited to small numbers or low densities of individuals. The main hurdle to tracking individuals over time is that, if they are not uniquely tagged, the identity of the trajectories will often switch when individuals interact. To allow for reliable long-term tracking of individuals in highly dense social environments researchers have augmented image analysis based strategies with unique identification tags. This includes tags such as colors [41] or QR codes (2D barcodes), which have now been deployed on ants [9, 27, 42], honey bees [43] and bumble bees [44]. Most of this work is confined to laboratory conditions. However, after validating tracking methods in the lab, those can be used in natural built structures.

2.2.2 Analyzing trajectories

Once trajectories are extracted from movement data, there have been many ways to quantify them. Examining speed, turning patterns, distance traveled, etc., all require simple computations. Determining where, when, and between whom, interactions occur is more complex [45]. Researchers often use proximity to determine if individuals interacted, however, that requires information about the study subject. For example, it is imperative to know how close two individuals need to be for an interaction to occur, how long they need to be in proximity for an interaction to be meaningful, and whether other behaviors need to be accounted for. Furthermore, there could be different types of interactions. In social insects, brief antennal interactions, and longer trophallactic interactions, are used for different purposes and only a few automated image analysis software can distinguish between the two [43]. In human studies, tracking hardware may capture audio so that communication can be recorded, or, at least, documented (e.g., who is speaking and for how long). A behavior that is often overlooked, but could be important, is stopping behavior. For example, animals stopped at certain locations may facilitate high frequency of interactions [46]. The locations where animals tend to stop, or slow down, could be dictated by the built environment. This could be due to a narrow passage way [46, 47] or, in the case of human structures, there could be an attractive feature, like a window, where humans may choose to stop and look at the view.

In most situations the interactions between individuals and their physical and social environment are tightly entangled. To connect a detailed quantitative description of individual-level interactions with the dynamics of motion observed at individual and group level, one has to adopt an incremental approach. Such an approach consists of first building a model, based on experiments, of the spontaneous motion of an isolated individual. The model is then used as a dynamical framework to include the effects of interactions of that individual with the physical environment and with neighboring individuals [48]. The agreement between the model's predictions and experiments on several observables in different conditions and group sizes can then be used to validate the model [45].

2.3 Linking the quantification of structures and movement

The true challenge we currently face is linking the quantification of structures and movements into one framework. First, the spatial scale of the built environment might be far greater than the spatial scale of the movements of each individual. For example, a single insect might have spatial fidelity to small regions of a large nest [44] so its movements will not be constrained by nest areas that it does not visit. One way around this challenge is by examining all the movements in aggregate, as done when using Space Syntax. Such aggregation has obvious tradeoffs, such as not being able to identify how much each individual contributes to the complexity of the observed movements. Furthermore, as mentioned above, built structures have cues other than the physical attributes, such as odors and auditory cues that might impact the relationship between the built environment and the movements within it.

A powerful method for linking the structure of the built environment with the movement and interaction patterns of its occupants is conducting experimental manipulations. Both animals and humans can be studied in different, predetermined, structures, and the structure attributes can be manipulated to make causative inference. In humans, such work can be done using virtual reality (VR), to reduce the costs of creating actual spaces [49]. The use of VR for such studies is still in its infancy and there is need for measuring physiological responses and comparing those to situations of movement in the real world in structures that are identical to the simulated one [50, 51].

Another way to link spatial and social networks is using a multilayer network framework [52]. In this framework networks which link different types of nodes can be connected through interlayer edges and the complete system can be analyzed in a single framework. This approach has been used to link different transportation modes. For example, including a layer for air transportation, a layer for train routes, and a layer for roads in a multilayer network can facilitate the identification of efficient travel paths by considering the various transportation modes simultaneously [53]. Similarly, one can link a network of social interactions with a network of spatial positions. Edges in the social network will describe social relationships that facilitate collective behaviors, edges in the spatial network will link connected places, and interlayer edges will link individuals to the locations where they spent time [52, 54, 55]. Such an approach is especially useful for large built structures in which each inhabitant occupies only a small part of the space.

3. Overview of contributed papers

This special issue aggregates empirical studies and review articles that showcase the current state of the art and explore future potential research directions that bring together architecture and collective behavior. We begin with a section on the effects of architecture on flow of information and disease, we continue with papers that showcase novel methods for advancing the quantification of both structures and the movements within them. Following are examples of how information gained from studies that combine a look at architecture and collective behavior can be implemented to improve policy and future designs and real-world applications. We conclude this special issue with a philosophical manuscript on the conceptual similarities and differences in the perception of architecture by humans and animals.

Built structures constrain the movements of the organisms inhabiting them, thus impacting the flow of information, ideas, and disease. The way information is impacted by the built environment is discussed in this special issue as a duet between an architect, Ireland, and a biologist, Garnier, in [56]. In their article, they re-examine the concepts of 'space' and 'information' to establish definitions spanning biology and architecture to enable cross-fertilization between these two disciplines. The authors discuss the informational content of constructions built by organisms and the influence these structures can have on the spatial and temporal organization of individual and collective behavior. This idea is reminiscent of the concept of stigmergy introduced by Pierre-Paul Grassé in 1959 to describe the coordinated building mechanisms of termites [57]. However, Ireland and Garnier [56] stage their paper in the frame of thought of enactivism, which considers that cognition arises from a dynamic interaction between an acting organism and its environment [58-60]. In this respect they make two important claims: (1) space is a fundamental form of information and (2) it is necessary to adopt a semiotic perspective to analyze and describe the influence of constructions on animal and human behavior. In other words, it is necessary to take into account the way that different species perceive the space and extract information from it through their specific sensory interfaces, to better understand the impact of architecture on their behavior.

By affecting the way individuals move and interact, the built environment can impact the spread of disease and information about health-promoting behaviors. The built environment can facilitate positive experiences, can increase longevity, and promote healthy behaviors, reducing chronic disease. In a review of the literature, Pinter-Wollman, Jelic, and Wells [61] discuss the ways in which the built environment can prevent and contain chronic and infectious disease in both humans and wildlife. They take an interdisciplinary approach that melds perspectives from the fields of architecture, social science, and biology. Interestingly, they find important parallels between the impact of built structure on humans and animals. For example, the materials that are chosen for building structures are often selected to promote hygiene. Furthermore, both humans and animals use the built environment to reduce interactions with sick individuals – either by quarantining them or by removing them from built structures. Differences between humans and animals include the idea that built structures may promote activity in humans to reduce chronic disease in humans. However, increasing activity can potentially decrease the lifespan of animals because activity might expose animals to dangers, such as predators. Therefore, built structures are used to protect certain individuals, such as ant queens, thus reducing their activity and increasing their lifespan.

These two review papers are followed by two empirical examples, one from humans and one from ground squirrels, of how the built environment can impact the flow of information and disease. In humans, Kabo and colleagues [62] show how characteristics of the built environment interact with social and organizational factors. Their paper combines data on spatial proximity with sociological questioners to evaluate how both spatial proximity and social connections influence perceived prestige of team projects. They find that spatial proximity correlates with social network structure and that this link impacts the perception of the prestige of the problem that a team is working on. This work points out how the centrality of an individual in a network can relate to cognition and collaboration via the access of individuals with high centrality to novel information. Further, centrality can be associated with one's physical location in an organizational setting. In particular, certain people may obtain their knowledge or status because they are located on shortest path between other pairs of coworkers. Interestingly, the less connected teams are considered to be working on more prestigious problems.

Ground squirrels are active both above and below ground. Above ground, squirrels forage for food and interact with each other with minimal physical constraints in their environment. However, in their extensive burrow system, interactions among colony members are restricted by the structure of their burrow. Using a novel tracking methods, Smith et al [63] uncover qualitative differences between the social networks that emerge above and below ground. These differences have important implications for how disease can be transferred between individuals depending on whether its transmission is restricted to the burrow system (e.g., through microorganisms that live inside the soil), or if transmission is through contacts, in which case, transmission dynamics will differ above- and below- ground because of the different emergent social structures.

As noted, understanding collective behavior and the built environment requires the quantification of structures, movements, and the combination of the two. In this issue, Varoudis et al [14] bring Space Syntax theory, which is used by architects of human dwellings, to describe the three dimensional structures that are excavated by ants inside acorns. This synergy between architects and biologists has led to the advancement of 2-dimentional methods used to study buildings of humans and expand it to the 3-dimentional space that ants occupy. Ants are not constrained to walking on the floor (as humans are) and so understanding the layout of all surfaces and dimensions in their nests could prove important for uncovering their collective behavior. The paper by Varoudis et al [14] provides a methodological breakthrough for both the examination of structures built by animals and for the expansion of space syntax.

In addition to quantifying the topology of structures, one needs to quantify the movements that happen in them. Studies of transportation are ahead in this respect because they have been studied for decades. Batty [8] provides a broad perspective on quantifying movement via examination of a human transportation patterns in, and between, cities, and explains how to represent aggregated movements in cities. This is a necessary first step along the path to determining what impacts these movement and the interactions between the moving individuals and in determining how space impacts these interactions. By providing visualization and analysis of movement patterns in physical space, Batty's work [8] opens up opportunities for further examination of the causes and consequences of these aggregate movements that could not be examined if the movements themselves were not quantifiable. Batty's work bridges between the geographical and architectural scales by focusing on the relationships between locations rather than on the role of each particular location. We are reminded that there are both temporal and spatial dynamics that need to be considered when quantifying movements because movement patterns can change according to the scale on which they are observed. For example, a short time window of a day might result in very different movement patterns if weekdays are compared to weekends.

The study of the effects of architecture on collective behavior would not be possible if structures were not built. In social insects, the building process is an emergent collective behavior that has been studied extensively both empirically and using modeling [64-73]. In this special issue we find out that the composition of the colony that is excavating a structure can substantially impact its topology [17]. In a polymorphic species of ant, *Veromessor pergandei*, smaller individuals build shorter and less complex nests than larger individuals. Most interestingly, mixed groups of both small and large individuals build nests that are larger and more complex than what would be expected by simply adding the behavior of the small and large individuals. Thus, there are non-linear effects that result in structures that one could not anticipate from simply adding the behavior of the different types of individuals in the colony. Understanding how the occupants of the built environment impact its structure is a first step in uncovering the continuous feedback between built structures and the collective behavior of the individuals that inhabit and build them.

Two studies to this special issue study real world interactions in diverse settings. Importantly, these studies link both theory and methods from different disciplines to converge on a unique view of how collective behavior is influenced by the context of interaction. Via a blend of social science theory and methods, along with electronic data and statistical modeling, these papers provide insights into how interactions of humans change due to the built environment.

Bernstein and Turbin [31] cover a persistent debate in organizational theory about how spatial boundaries in offices influence collective behavior and various organizational outcomes. As originally argued, social science theory suggested that open plan offices would increase contact between employees and improve social interactions. These improved social interactions would then improve organizational outcomes – from the attitudinal (e.g., cohesion) to the behavioral (e.g., communication and information exchange). These organizational outcomes can then enhance collective intelligence that could be leveraged to improve organizational performance. The findings on open plan offices are mixed with many studies finding a lack of employee satisfaction with these architectural design changes. In a unique study combining digital data of physical interactions with electronic communications, Bernstein and Turbin [31] study what happens when organizations change from traditional workspace design to open office architectures. Across two separate studies, with different organizations, they find consistent results. By examining physical interactions and electronic communications simultaneously, they are able to uncover how a move to open offices counter-intuitively decreases face-to-face interactions while increasing electronic interactions. Further, their data suggest that organizational productivity decreased with the move to an open office. This paper makes an important contribution by providing a robust methodology to continue research on how architectural designs influence collective behavior.

With an innovative combination of theory and context, Alnabulsi and colleagues [74] study the annual Hajj to Mecca and examine how the built environment interacts with ritualistic behavior and beliefs. Attended by millions of pilgrims, the Hajj is truly a unique setting for examining architecture and its influence on crowds. Through analyses of crowd density, coupled with survey methodology, Alnabulsi et al [74] study collective behavior through the lens of cooperative behavior. They examine the psychological processes related to the social support experienced by pilgrims and uncover how identification with others determines the form of behavior exhibited. Drawing from social identity theory, they interpret differences in providing social support when pilgrims are inside the Mosque area versus in the plaza. The differences in density between these two physical spaces, as well as differences in their ritualistic significance, represent how cultural aspects of the built environment can influence collective behavior.

Last, Turner and Penn [75] provide interdisciplinary theorizing as a way to integrate many of the concepts across the biological, cognitive, and social sciences. They draw from theories of embodied and extended cognition theory, and integrate these with niche construction theory arising out of the biological sciences. With this, they link developments in biomimetic architecture to identify general architectural principles. Their goal is to point the way forward to unifying research and theory across not only a variety of disciplines, but also across taxa and spatial scales.

4. A path forward

To guide thinking on the integration of concepts and methods, we provide below a set of general research questions and approaches to assist in the integration of research on the built environment, movement, interactions, and collective behavior. A recent issue in this journal presented many advances to the study of collective movement [76]. However, the study of collective movement often overlooks the impact of physical constraints. Rather, it focuses on the coordination of actions among individuals to produce collective movements. As seen in this special issue, we propose that adding a further examination of the effects of spatial constraints on collective actions, in particular the constraints imposed by the structures built by the organisms themselves (or other organisms), can add a novel, important, and often overlooked factor in determining the emergence of collective behavior. As detailed above and seen in the articles in this special issue, such an examination requires the quantification of structures, movements, and the combination of the two. In light of this, we offer research questions and approaches that provide a way to address these needs via interdisciplinary research.

First, the quantification of structures requires the development of innovations to extract spatial attributes as well as describe the geometry of spaces. To guide these ventures, one might consider identifying cross-disciplinary constructs and/or methods that can be adapted to illuminate universals in structural design that influence collective behavior. To quantify the various aspects of built structures it might be fruitful to combine features of network theory with concepts from space syntax, to achieve a rich formulation of methods to quantify geometric features that influence collective behavior.

Second, when considering the quantification of movements within structures, there is the need to develop innovations for extracting movement patterns, analyzing trajectories, and linking these. Novel technological developments to track movement patterns continue to emerge, and working with engineers to implement and utilize new technologies can advance our understanding of how architecture influences collective behavior. Furthermore, borrowing methods from movement ecology [76] and adapting them to smaller spatial scales with physical constraints can provide the tools necessary for quantifying movements.

Finally, the biggest challenge we anticipate is merging the examination of space and of movements into one framework to determine how these two interact to impact the emergence of collective behaviors. For example, one can consider different scales of movements and ask how can complementarity tracking techniques be expanded to integrate design-, architectural-, and geographical- level of the built environment. Such integration will allow the examination of how each level separately and/or all levels together impact movement patterns and collective behavior. Cross-disciplinary methods may be used to disentangle the physical and social environment to advance theoretical understanding and empirical approaches for understanding how architecture influences collective behavior. Finally, interdisciplinary research may develop a multi-modal and multi-sensory framework to capturing the varieties of signals communicated in different types of spaces, creating a link between the build environment and the behavior of the occupants.

5. Conclusions

This themed issue serves as an important foundation for a new line of interdisciplinary research on the effects of architecture on collective behavior. By bringing together biologists, social scientists, and architects, we expect to inspire new research questions and theoretical frameworks both within and across these disciplines. The exchange of methods, theory, and concepts across disciplines seen in this special issue will hopefully lead to novel scientific studies that cross traditional disciplinary boundaries.

Our hope is that the questions we raise, viewed in light of the contributions of this special issue, can be used to guide an interdisciplinary science of architecture and collective behavior. Doing so can have far reaching scientific and practical implications. From the scientific standpoint, this can help us identify design universals in architecture that have evolved out of the animal kingdom and may occur across species. From the practical standpoint, this can help us develop guidelines for novel designs of spaces that foster collective behavior, enhance collaboration, and facilitate development of new forms of emergent cognition. Such innovative spaces can have substantial social and/or economic implications through the promotion of cohesion, creativity, and effective teamwork.

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