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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 90095, USA
[2]The Bartlett Faculty of the Built Environment, University College London, London WC1H 0QB, UK
[3]Centre de Recherches sur la Cognition Animale, Centre de Biologie Intégrative, CNRS, Université de Toulouse, 31062 Toulouse, France
[4]Department of Philosophy and the Institute for Simulation and Training, University of Central Florida, Orlando, FL 32826, USA

NP-W, 0000-0002-0448-8037; AP, 0000-0003-3793-8134; GT, 0000-0002-3062-4215

Introduction

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Author for correspondence:
Noa Pinter-Wollman
e-mail: nmpinter@ucla.edu

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 behaviour expands, it is time to elucidate the role of the built environment in shaping collective outcomes. Collective behaviour 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 behaviour or collective cognition. An interdisciplinary exchange between behavioural 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 behaviour. This article, along with those in this theme issue aims to formalize and catalyse this interdisciplinary exchange.

This article is part of the theme issue 'Interdisciplinary approaches for uncovering the impacts of architecture on collective behaviour'.

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 behaviour of colonies [1]; research in social and cognitive sciences on humans has begun to investigate how buildings or environmental factors can alter social behaviour [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 behaviours, there has been little, if any, interdisciplinary communication among these research communities. This theme 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 theme issue point us towards

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innovations that can advance our understanding of how to study these forms of complex collaborations (cf. [7]).

The contributions to this theme 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 behaviour, as some of the papers in this theme issue have begun to do. We then outline the structure of the theme issue and highlight the findings of the contributed papers. To bring together the methodological approaches and insights from the contributed papers, we conclude with a set of general research questions for readers to consider. In service of developing an interdisciplinary science of architecture and collective behaviour, 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 behaviour

To study the impact of architecture on collective behaviour, 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 behaviours. Here, we outline some of the methods used to obtain and describe these types of spatial and behavioural data and the quantitative approaches that have been used to analyse it.

(a) Quantifying structures

To determine the impact of the built environment on collective behaviours, 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 'geographical 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, odours and acoustics can impact the way individuals interact [9]. Social insects relay on the odour of the chambers they occupy to determine what type of task is performed in them [10]. Acoustic signals, such as stridulating, can shape the way social insects move in their nest and structure them [11]. Noise can impact the communication between humans and odours in the environment may prevent or promote the use of certain areas in a building. Thus, an 'odour 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 odour, all important modes of communication for social communities.

(i) Extracting spatial attributes

Architects design the built environments that humans occupy, meaning that blueprints and other such representations (e.g. diagrams and 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 aluminium [12], concrete and expanding foam [13]. 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 [13–15]. The three-dimensional 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 of 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.

(ii) 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 [13,16] 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 [14], spatial overlap between occupants [2], structural robustness [1,17], number of junctions [18], etc. In network depiction of structures, corridors or tunnels are usually network edges and rooms or chambers are often the network nodes [1,2,18], but sometimes tunnel junctions are represented as network nodes [19,20]. Once a structure is represented as a network, one can use a wide range of network measures to quantify the structure and its properties [21]. Some of these measures include local connectivity (e.g. centrality of particular nodes or edges [22]), global connectivity (e.g. average degree of all nodes [18]), meshedness (the proportion of cycles in the network [20]), path overlap [2], accessibility (number of nodes in the network that can be reached in exactly h steps from a given node [22]) 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 Hillier & Hanson [23]. 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 [24], and the product of these patterns of movement in terms of co-presence in space and communication between people [25].

(b) 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 [26–29]. After movement patterns are extracted, they need to be analysed to gain insights about the behaviour 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 [30].

(i) Extracting movement patterns

Similarly to when quantifying structures, one first needs a description of movements before they can be analysed. 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 [31,32]. Similarly, the movement of ants has been tracked using RFID tags [27]. 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 [32] and animals [33], 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 [34,35].

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 [36–38], and animals (www.antracks.org, www.noldus.com) [39]. 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 colours [40] or QR codes (two-dimensional barcodes), which have now been deployed on ants [10,28,41], honeybees [42] and bumblebees [43]. Most of this work is confined to laboratory conditions. However, after validating tracking methods in the laboratory, those can be used in natural built structures.

(ii) Analysing trajectories

Once trajectories are extracted from movement data, there have been many ways to quantify them. Examining speed, turning patterns, distance travelled, etc., all require simple computations. Determining where, when and between whom, interactions occur is more complex [44]. 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 behaviours 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 [42]. 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) [32]. A behaviour that is often overlooked, but could be important, is stopping behaviour. For example, animals stopped at certain locations may facilitate high frequency of interactions [45]. 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 [45,46] or, in the case of human structures, there could be some feature that leads people to gather, like a water cooler, where humans may discuss work [47].

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 neighbouring 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 [44].

(c) 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 [43], 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 trade-offs, 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 odours 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 a 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 that link different types of nodes can be connected through interlayer edges and the complete system can be analysed 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 behaviours, 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 theme 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 behaviour. 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 behaviour can be implemented to improve policy and future designs. We conclude this theme 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 theme 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 behaviour. 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, Garnier & Ireland [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: (i) space is a fundamental form of information and (ii) it is necessary to adopt a semiotic perspective to analyse and describe the influence of constructions on animal and human behaviour. 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 behaviour.

By affecting the way individuals move and interact, the built environment can impact the spread of disease and information about health-promoting behaviours. The built environment can facilitate positive experiences, can increase longevity and promote healthy behaviours, reducing chronic disease. In a review of the literature, Pinter-Wollman *et al.* [61] discuss the ways in which the built environment can prevent and contain the 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 [62] shows how characteristics of the built environment interact with social and organizational factors. His paper combines data on spatial proximity with survey questions on employee perceptions, to evaluate how both spatial proximity and social connections influence perceived prestige of team projects. He finds that spatial proximity correlates with social network structure and that this link impacts the perception of the prestige of the problem on which a team is working. 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 the shortest route between other pairs of co-workers. Interestingly, 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 method, Smith *et al.* [63] uncover 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 behaviour and the built environment requires the quantification of structures, movements and the combination of the two. In this issue, Varoudis *et al.* [15] bring the first application, to our knowledge, of Space Syntax to the study of an animal structure. Traditionally used by architects and the study of human dwellings, here Space Syntax theory is used 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 two-dimensional methods used to study buildings of humans and expand it to the three-dimensional 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 behaviour. The paper by Varoudis *et al.* [15] 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 human transportation has been studied for decades. Batty [8] provides a broad perspective on quantifying movement via examination of 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 movements 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 behaviour would not be possible if structures were not built. In social insects, the building process is an emergent collective behaviour that has been studied extensively both empirically and using modelling [64–73]. In this theme issue, Kwapich *et al.* [19] show that the composition of the colony that is excavating a structure can substantially impact nest topology. 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 behaviour of the small and large individuals. Thus, there are nonlinear effects that result in structures that one could not anticipate from simply adding the behaviour 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 behaviour of the individuals that inhabit and build them.

Two studies in this theme issue study human interactions in diverse settings. Importantly, these studies link theory and methods from different disciplines to converge on a novel view of how collective behaviour is influenced by the context of interactions. Via a blend of social science theory and methods, along with electronic data and statistical modelling, these papers provide insights into how human interactions change due to the built environment.

Bernstein & Turban [32] cover a persistent debate in organizational theory about how spatial boundaries in offices influence collective behaviour and various organizational outcomes. Originally, 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 behavioural (e.g. communication and information exchange). These organizational outcomes might 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 & Turban [32] 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 counterintuitively 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 behaviour.

With an innovative combination of theory and context, Alnabulsi *et al.* [74] study the annual Hajj to Mecca and examine how the built environment interacts with ritualistic behaviour and beliefs. Attended by millions of pilgrims, the Hajj is 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 behaviour through the lens of cooperative behaviour. They examine the psychological processes related to the social support experienced by pilgrims and uncover how identification with others determines the form of behaviour 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, illustrate how cultural aspects of the built environment can influence collective behaviour.

Last, Penn & Turner [75] provide interdisciplinary theorizing as a way to integrate many of the concepts across the biological, cognitive and social sciences. They draw from embodied and extended cognition theory, and integrate these with niche construction theory arising from 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 behaviour. A recent issue of 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 theme issue, we propose that including 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 behaviour. As detailed above and seen in the articles in this theme 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 behaviour. 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 behaviour.

Second, when considering the quantification of movements within structures, there is need to develop innovations for extracting movement patterns, analysing trajectories and linking these. Novel technological developments to track movement patterns continue to emerge, and working with engineers to implement and use new technologies can advance our understanding of how architecture influences collective behaviour. 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 behaviours. For example, one can consider different scales of movements and ask how can complementary tracking techniques be expanded to integrate design-, architectural- and geographical-scales 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 behaviour. 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 behaviour. 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 built environment and the behaviour of the occupants.

5. Conclusion

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

Our hope is that the questions we raise, viewed in the light of the contributions of this theme issue, can be used to guide an interdisciplinary science of architecture and collective behaviour. 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 in 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 behaviour, 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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Endnote

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References

1. Pinter-Wollman N. 2015 Nest architecture shapes the collective behaviour of harvester ants. *Biol. Lett.* **11**, 20150695. (doi:10.1098/rsbl.2015.0695)
2. Kabo FW, Cotton-Nessler N, Hwang YH, Levenstein MC, Owen-Smith J. 2014 Proximity effects on the dynamics and outcomes of scientific collaborations. *Res. Pol.* **43**, 1469–1485. (doi:10.1016/j.respol.2014.04.007)
3. Birnholtz JP, Gutwin C, Hawkey K. 2007 Privacy in the open: how attention mediates awareness and privacy in open-plan offices. In *Group'07: Proc. of the 2007 Int. Acm Conf. on Supporting Group Work*, Sanibel Island, FL, USA, 4–7 November 2007, pp. 51–60. New York, NY: ACM.
4. Vischer JC. 2008 Towards an environmental psychology of workspace: how people are affected

by environments for work. *Archit. Sci. Rev.* **51**, 97–108. (doi:10.3763/asre.2008.5114)

5. Fiore SM. 2008 Interdisciplinarity as teamwork—how the science of teams can inform team science. *Small Gr. Res.* **39**, 251–277. (doi:10.1177/1046496408317797)
6. Fiore SM, Rosen MA, Smith-Jentsch KA, Salas E, Letsky M, Warner N. 2010 Toward an understanding of macrocognition in teams: predicting processes in complex collaborative contexts. *Hum. Factors* **52**, 203–224. (doi:10.1177/0018720810369807)
7. Hall KL, Vogel AL, Huang GC, Serrano KL, Rice EL, Tsakraklides S, Fiore SM. 2018 The science of team science: a review of the empirical evidence and research gaps on collaboration in science. *Am. Psychol.* **73**, 532–548. (doi:10.1037/amp0000319)
8. Batty M. 2018 Visualizing aggregate movement in cities. *Phil. Trans. R. Soc. B* **373**, 20170236. (doi:10.1098/rstb.2017.0236)
9. Casellas E, Gautrais J, Fournier R, Blanco S, Combe M, Fourcassié V, Theraulaz G, Jost C. 2008 From individual to collective displacements in heterogenous environments. *J. Theor. Biol.* **250**, 424–434. (doi:10.1016/j.jtbi.2007.10.011)
10. Heyman Y, Shental N, Brandis A, Hefetz A, Feinerman O. 2017 Ants regulate colony spatial organization using multiple chemical road-signs. *Nat. Commun.* **8**, 15414. (doi:10.1038/ncomms15414)
11. Pielstrom S, Roces F. 2012 Vibrational communication in the spatial organization of collective digging in the leaf-cutting ant *Atta vollenweideri*. *Anim. Behav.* **84**, 743–752. (doi:10.1016/j.anbehav.2012.07.008)
12. Tschinkel WR. 2010 Methods for casting subterranean ant nests. *J. Insect Sci.* **10**, 88. (doi:10.1673/031.010.8801)
13. Weber JN, Hoekstra HE. 2009 The evolution of burrowing behaviour in deer mice (genus *Peromyscus*). *Anim. Behav.* **77**, 603–609. (doi:10.1016/j.anbehav.2008.10.031)
14. Perna A, Valverde S, Gautrais J, Jost C, Sole R, Kuntz P, Theraulaz G. 2008 Topological efficiency in three-dimensional gallery networks of termite nests. *Physica A* **387**, 6235–6244. (doi:10.1016/j.physa.2008.07.019)
15. Varoudis T, Swenson AG, Kirkton SD, Waters JS. 2018 Exploring nest structures of acorn dwelling ants with X-ray microtomography and surface-based three-dimensional visibility graph analysis. *Phil. Trans. R. Soc. B* **373**, 20170237. (doi:10.1098/rstb.2017.0237)
16. Perna A, Jost C, Couturier E, Valverde S, Douady S, Theraulaz G. 2008 The structure of gallery networks in the nests of termite *Cubitermes* spp. revealed by X-ray tomography. *Naturwissenschaften* **95**, 877–884. (doi:10.1007/s00114-008-0388-6)
17. Tschinkel WR. 2011 Back to basics: sociometry and sociogenesis of ant societies (Hymenoptera: Formicidae). *Myrmecol News* **14**, 49–54.
18. Buhl J, Gautrais J, Sole RV, Kuntz P, Valverde S, Deneubourg JL, Theraulaz G. 2004 Efficiency and robustness in ant networks of galleries. *Eur. Phys. J. B* **42**, 123–129. (doi:10.1140/epjb/e2004-00364-9)
19. Kwapich CL, Valentini G, Hölldobler B. 2018 The non-additive effects of body size on nest architecture in a polymorphic ant. *Phil. Trans. R. Soc. B* **373**, 20170235. (doi:10.1098/rstb.2017.0235)
20. Buhl J, Gautrais J, Deneubourg JL, Theraulaz G. 2004 Nest excavation in ants: group size effects on the size and structure of tunneling networks. *Naturwissenschaften* **91**, 602–606. (doi:10.1007/s00114-004-0577-x)
21. Barthelemy M. 2017 *Morphogenesis of spatial networks*. New York, NY: Springer Berlin Heidelberg.
22. Viana MP, Fourcassie V, Perna A, Costa LD, Jost C. 2013 Accessibility in networks: a useful measure for understanding social insect nest architecture. *Chaos Soliton Fract.* **46**, 38–45. (doi:10.1016/j.chaos.2012.11.003)
23. Hillier B, Hanson, J. 1984 *The social logic of space*. Cambridge, UK: Cambridge University Press.
24. Hillier B, Penn A, Hanson J, Grajewski T, Xu J. 1993 Natural movement—or, configuration and attraction in urban pedestrian movement. *Environ. Plann. B* **20**, 29–66. (doi:10.1068/b200029)
25. Penn A, Desyllas J, Vaughan L. 1999 The space of innovation: interaction and communication in the work environment. *Environ. Plann. B* **26**, 193–218. (doi:10.1068/b4225)
26. Moreau M, Arrufat P, Latil G, Jeanson R. 2011 Use of radio-tagging to map spatial organization and social interactions in insects. *J. Exp. Biol.* **214**, 17–21. (doi:10.1242/jeb.050526)
27. Jeanson R. 2012 Long-term dynamics in proximity networks in ants. *Anim. Behav.* **83**, 915–923. (doi:10.1016/j.anbehav.2012.01.009)
28. Mersch DP, Crespi A, Keller L. 2013 Tracking individuals shows spatial fidelity is a key regulator of ant social organization. *Science* **340**, 1090–1093. (doi:10.1126/science.1234316)
29. Batty M. 1997 Predicting where we walk. *Nature* **388**, 19–20. (doi:10.1038/40266)
30. Pinter-Wollman N, Bala A, Merrell A, Queirolo J, Stumpe MC, Holmes S, Gordon DM. 2013 Harvester ants use interactions to regulate forager activation and availability. *Anim. Behav.* **86**, 197–207. (doi:10.1016/j.anbehav.2013.05.012)
31. Salathé M, Kazandjieva M, Lee JW, Levis P, Feldman MW, Jones JH. 2010 A high-resolution human contact network for infectious disease transmission. *Proc. Natl Acad. Sci. USA* **107**, 22 020–22 025. (doi:10.1073/pnas.1009094108)
32. Bernstein ES, Turban S. 2018 The impact of the ‘open’ workspace on human collaboration. *Phil. Trans. R. Soc. B* **373**, 20170239. (doi:10.1098/rstb.2017.0239)
33. Barocas A, Golden HN, Harrington MW, McDonald DB, Ben-David M. 2016 Coastal latrine sites as social information hubs and drivers of river otter fission–fusion dynamics. *Anim. Behav.* **120**, 103–114. (doi:10.1016/j.anbehav.2016.07.016)
34. Robinson EJH, Richardson TO, Sendova-Franks AB, Feinerman O, Franks NR. 2008 Radio tagging reveals the roles of corpulence, experience and social information in ant decision making. *Behav. Ecol. Sociobiol.* **63**, 627–636. (doi:10.1007/s00265-008-0696-z)
35. Sorensen A, van Beest FM, Brook RK. 2014 Impacts of wildlife baiting and supplemental feeding on infectious disease transmission risk: a synthesis of knowledge. *Prev. Vet. Med.* **113**, 356–363. (doi:10.1016/j.prevetmed.2013.11.010)
36. Marana AN, Cavenaghi MA, Ulson RS, Drumond FL. 2005 Real-time crowd density estimation using images. In *Advances in Visual Computing. ISVC 2005. Lecture Notes in Computer Science, vol. 3804* (eds G Bebis, R Boyle, D Koracin, B Parvin), pp. 355–362. Berlin, Heidelberg: Springer-Verlag. (doi:10.1007/11595755_43)
37. Kratz L, Nishino, K. 2012 Going with the flow: pedestrian efficiency in crowded scenes. *Comput. Vis.* **7575**, 558–572. (doi:10.1007/978-3-642-33765-9_40)
38. Bera A, Galoppo N, Sharlet D, Lake A, Manocha D. 2014 AdaPT: real-time adaptive pedestrian tracking for crowded scenes. *Ieee Int. Conf. Robot.* 1801–1808. (doi:10.1007/978-3-642-33765-9_40)
39. Perez-Escudero A, Vicente-Page J, Hinz RC, Arganda S, de Polavieja GG. 2014 idTracker: tracking individuals in a group by automatic identification of unmarked animals. *Nat. Methods* **11**, 743–748. (doi:10.1038/nmeth.2994)
40. Pinter-Wollman N, Hubler J, Holley JA, Franks NR, Dornhaus A. 2012 How is activity distributed among and within tasks in *Temnothorax* ants? *Behav. Ecol. Sociobiol.* **66**, 1407–1420. (doi:10.1007/s00265-012-1396-2)
41. Greenwald E, Segre E, Feinerman O. 2015 Ant trophallactic networks: simultaneous measurement of interaction patterns and food dissemination. *Sci. Rep.* **5**, 12496. (doi:10.1038/srep12496)
42. Gernat T, Rao VD, Middendorf M, Dankowicz H, Goldenfeld N, Robinson GE. 2018 Automated monitoring of behavior reveals bursty interaction patterns and rapid spreading dynamics in honeybee social networks. *Proc. Natl Acad. Sci. USA* **115**, 1433–1438. (doi:10.1073/pnas.1713568115)
43. Crall JD, Gravish N, Mountcastle AM, Kocher SD, Oppenheimer RL, Pierce NE, Combes SA. 2018 Spatial fidelity of workers predicts collective response to disturbance in a social insect. *Nat. Commun.* **9**, 1201. (doi:10.1038/s41467-018-03561-w)
44. Calovi DS, Litchinko A, Lecheval V, Lopez U, Escudero AP, Chate H, Sire C, Theraulaz G. 2018 Disentangling and modeling interactions in fish with burst-and-coast swimming reveal distinct alignment and attraction behaviors. *PLoS Comput. Biol.* **14**, e1005933 (doi:10.1371/journal.pcbi.1005933)
45. Pinter-Wollman N, Wollman R, Guetz A, Holmes S, Gordon DM. 2011 The effect of individual variation on the structure and function of interaction networks in harvester ants. *J. R. Soc. Interface* **8**, 1562–1573. (doi:10.1098/rsif.2011.0059)
46. Burd M, Shiwakoti N, Sarvi M, Rose G. 2010 Nest architecture and traffic flow: large potential effects from small structural features. *Ecol. Entomol.* **35**, 464–468. (doi:10.1111/j.1365-2311.2010.01202.x)

47. Kraut RE, Streeter LA. 1995 Coordination in software development. *Comm. ACM* **38**, 69–81. (doi:10.1145/203330.203345)
48. Gautrais J, Ginelli F, Fournier R, Blanco S, Soria M, Chate H, Theraulaz G. 2012 Deciphering interactions in moving animal groups. *PLoS Comput. Biol.* **8**, e1002678. (doi:10.1371/journal.pcbi.1002678)
49. Rio KW, Dachner GC, Warren WH. 2018 Local interactions underlying collective motion in human crowds. *Proc. R. Soc. B* **285**, 20180611. (doi:10.1098/rspb.2018.0611)
50. Moussaid M, Kapadia M, Thrash T, Sumner RW, Gross M, Helbing D, Holscher C. 2016 Crowd behaviour during high-stress evacuations in an immersive virtual environment. *J. R. Soc. Interface* **13**, 20160414. (doi:10.1098/rsif.2016.0414)
51. Stowers JR *et al.* 2017 Virtual reality for freely moving animals. *Nat. Methods* **14**, 995. (doi:10.1038/nmeth.4399)
52. Kivelä M, Arenas A, Barthelemy M, Gleeson JP, Moreno Y, Porter MA. 2014 Multilayer networks. *J. Complex Netw.* **2**, 203–271. (doi:10.1093/comnet/cnu016)
53. Gallotti R, Barthelemy M. 2015 The multilayer temporal network of public transport in Great Britain. *Sci. Data* **2**, 140056. (doi:10.1038/sdata.2014.56)
54. Silk MJ, Finn KR, Porter MA, Pinter-Wollman N. 2018 Can multilayer networks advance animal behavior research? *Trend Ecol. Evol.* **33**, 6. (doi:10.1016/j.tree.2018.03.008)
55. Finn KR, Silk MJ, Porter MA, Pinter-Wollman, N. 2018 Novel insights into animal sociality from multilayer networks. (http://arxiv.org/abs/1712.01790)
56. Ireland T, Garnier S. 2018 Architecture, space and information in constructions built by humans and social insects: a conceptual review. *Phil. Trans. R. Soc. B* **373**, 20170244. (doi:10.1098/rstb.2017.0244)
57. Grassé PP. 1959 La reconstruction du nid et les coordinations interindividuelles chez *Bellicositermes natalensis* et *Cubitermes* sp. La theorie de la stigmergie: essai d'interpretation du comportement des termites constructeurs. *Insectes Sociaux Paris* **6**, 41–83. (doi:10.1007/bf02223791)
58. Varela FJ. 1979 *Principles of biological autonomy*. New York, NY: Eleviser.
59. Thompson E. 2007 *Mind in life: biology, phenomenology, and the sciences of mind*. Cambridge, MA: Belknap Press of Harvard University Press.
60. Brentari C. 2015 *Jakob von Uexkull: the discovery of the umwelt between biosemiotics and theoretical biology*. New York, NY: Springer.
61. Pinter-Wollman N, Jelić A, Wells NM. 2018 The impact of the built environment on health behaviours and disease transmission in social systems. *Phil. Trans. R. Soc. B* **373**, 20170245. (doi:10.1098/rstb.2017.0245)
62. Kabo F. 2018 The architecture of *network collective intelligence*: correlations between social network structure, spatial layout and prestige outcomes in an office. *Phil. Trans. R. Soc. B* **373**, 20170238. (doi:10.1098/rstb.2017.0238)
63. Smith JE, Gamboa DA, Spencer JM, Travenick SJ, Ortiz CA, Hunter RD, Sih A. 2018 Split between two worlds: automated sensing reveals links between above- and belowground social networks in a free-living mammal. *Phil. Trans. R. Soc. B* **373**, 20170249. (doi:10.1098/rstb.2017.0249)
64. Khuong A, Gautrais J, Perna A, Sbai C, Combe M, Kuntz P, Jost C, Theraulaz G. 2016 Stigmergic construction and topochemical information shape ant nest architecture. *Proc. Natl Acad. Sci. USA* **113**, 1303–1308. (doi:10.1073/pnas.1509829113)
65. Buhl J, Deneubourg JL, Grimal A, Theraulaz G. 2005 Self-organized digging activity in ant colonies. *Behav. Ecol. Sociobiol.* **58**, 9–17. (doi:10.1007/s00265-004-0906-2)
66. Gautrais J, Buhl J, Valverde S, Kuntz P, Theraulaz G. 2014 The role of colony size on tunnel branching morphogenesis in ant nests. *PLoS ONE* **9**, e109436. (doi:10.1371/journal.pone.0109436)
67. Theraulaz G, Bonabeau E. 1995 Modelling the collective building of complex architectures in social insects with lattice swarms. *J. Theor. Biol.* **177**, 381–400. (doi:10.1006/jtbi.1995.0255)
68. Theraulaz G, Bonabeau E. 1995 Coordination in distributed building. *Science* **269**, 686–688. (doi:10.1126/science.269.5224.686)
69. Bonabeau E, Theraulaz G, Deneubourg JL, Franks NR, Rafelsberger O, Joly JL, Blanco S. 1998 A model for the emergence of pillars, walls and royal chambers in termite nests. *Phil. Trans. R. Soc. Lond. B* **353**, 1561–1576. (doi:10.1098/rstb.1998.0310)
70. Ladley D, Bullock S. 2005 The role of logistic constraints in termite construction of chambers and tunnels. *J. Theor. Biol.* **234**, 551–564. (doi:10.1016/j.jtbi.2004.12.012)
71. Toffin E, Di Paolo D, Campo A, Detrain C, Deneubourg JL. 2009 Shape transition during nest digging in ants. *Proc. Natl Acad. Sci. USA* **106**, 18 616–18 620. (doi:10.1073/pnas.0902685106)
72. Franks NR, Wilby A, Silverman BW, Tofts C. 1992 Self-organizing nest construction in ants—sophisticated building by blind bulldozing. *Anim. Behav.* **44**, 357–375. (doi:10.1016/0003-3472(92)90041-7)
73. Franks NR, Deneubourg JL. 1997 Self-organizing nest construction in ants: individual worker behaviour and the nest's dynamics. *Anim. Behav.* **54**, 779–796. (doi:10.1006/anbe.1996.0496)
74. Alnabulsi H, Drury J, Templeton A. 2018 Predicting collective behaviour at the Hajj: place, space and the process of cooperation. *Phil. Trans. R. Soc. B* **373**, 20170240. (doi:10.1098/rstb.2017.0240)
75. Penn A, Turner JS. 2018 Can we identify general architectural principles that impact the collective behaviour of both human and animal systems? *Phil. Trans. R. Soc. B* **373**, 20180253. (doi:10.1098/rstb.2018.0253)
76. Westley PAH, Berdahl AM, Torney CJ, Biro D. 2018 Collective movement in ecology: from emerging technologies to conservation and management. *Phil. Trans. R. Soc. B* **373**, 20170004. (doi:10.1098/rstb.2017.0004)