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Noa Pinter-Wollman, Stephen M Fiore, Guy Theraulaz

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1 **The impact of architecture on collective behavior**

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3 Noa Pinter-Wollman<sup>1</sup>, Stephen M. Fiore<sup>2</sup>, and Guy Theraulaz<sup>3</sup>

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5 1. Department of Ecology and Evolutionary Biology, University of California, Los Angeles (nmpinter@ucla.edu)

6 2. Philosophy Department and the Institute for Simulation & Training, University of Central Florida, Orlando, FL  
7 32826 USA (sfiore@ist.ucf.edu)

8 3. Centre de Recherches sur la Cognition Animale, UMR-CNRS 5169, Universit Paul Sabatier, 31062 Toulouse  
9 Cedex 9, France. (guy.theraulaz@univ-tlse3.fr)

10  
11 **Abstract:** Collective behavior emerges from social interactions among group members. Despite the obvious  
12 influence of space on interactions, constraints imposed by the built environment are seldom considered when  
13 examining collective behaviors of animals and humans. We propose an interdisciplinary path towards uncovering  
14 the impact of architecture on collective outcomes.

15  
16 Built structures, such as animal nests, serve two overarching purposes: shelter and a space where organisms  
17 interact. The former has dominated much of the discussion in the literature <sup>1</sup>. But, as the study of collective  
18 behavior expands, it is time to elucidate the role of the built environment in shaping collective outcomes.

19 Collective behavior of social animals emerges from interactions <sup>2</sup> and collective cognition of humans  
20 emerges from communication and coordination <sup>3</sup>. Despite the obvious influence of space on interactions, because  
21 spatial proximity is necessary for an interaction to occur, spatial constraints are rarely considered in studies of  
22 collective behavior. An interdisciplinary exchange between behavioral ecologists, evolutionary biologists, cognitive  
23 scientists, and architects may facilitate a productive exchange of ideas, methods, and theory that could lead us to  
24 uncover unifying principles and novel research approaches and questions in studies of animal and human behavior.

25 For example, experiments on the impact of structures on the collective behavior of animals can inspire architects  
26 to design spaces that facilitate collective movements, interactions, collaboration, and innovation of humans. An  
27 increased understanding of the effects of structural constraints on interactions is now possible because of new  
28 tracking tools used in conjunction with complex network theory (Box 1). Here we suggest research questions that  
29 will benefit from both interdisciplinary exchange and recent technological advances.

30

### 31 **Collective cognition and efficiency**

32 Work on the impact of architecture on collective outcomes has already provided preliminary accounts of how  
33 structures influence the efficiency of collective behavior in animals and collective cognition in humans. Biologists  
34 have found that the speed at which harvester ants recruit to food increases with the connectivity of nest chambers  
35 <sup>4</sup> and that obstructions near the nest exit of ants facilitate rapid evacuation when in distress <sup>5</sup>. Social scientists  
36 have found that the layout of buildings affects scientific collaborations <sup>6</sup> and innovation <sup>7</sup>. Despite conceptual  
37 similarities among these research communities, there has been little, if any, cross-disciplinary communication.  
38 Although there are differences among organisms that occupy built structures (e.g., social insects prefer dark spaces  
39 and humans prefer light), there are functional similarities, such as the need to coordinate activities and  
40 collaborate, which can be extended from one discipline to inform the other. In particular, examining the behavior  
41 of animals lends itself to conducting experimental manipulations that are not feasible with human societies. Thus,  
42 testing and manipulating social structures and group interactions in social animals, may provide insights on the  
43 causative relationships between certain architectural features and collective outcomes that can then be used to  
44 improve the efficiency of human societies.

45

### 46 **Information processing**

47 When group members interact to produce collective outcomes there is information exchange and processing.  
48 Physical structures can serve an important functional role in this information processing. First, structures can help  
49 manage the volume and diffusion of information. Larger spaces afford greater amounts of information to be

50 transmitted. However, being exposed to too much information simultaneously can be overwhelming and cause  
51 individuals to shut down and reduce interactions with their surroundings<sup>8</sup>. Thus, structures that segregate  
52 individuals (e.g., chambers and tunnels), may reduce stimuli and help filter unnecessary information. Second,  
53 certain spatial cues, such as the chemical trails of social insects and road signs in human transportation networks,  
54 can aid in the interpretation and use of information. Such cues in the environment can help avoid information  
55 overload by externalizing knowledge that can then be used as a scaffold for further information building. Despite  
56 the economic implications of such structures (furniture, signs, obstacles etc.) on work productivity in humans,  
57 there has been little quantitative research on how spatial layouts and physical artifacts can influence collective  
58 information processing. By manipulating spatial signals and physical obstacles to examine their impact on the  
59 collective actions of social animals, we can develop new, biologically inspired, means to improve information  
60 processing in humans.

61

## 62 **Feedback between structure and behavior**

63 Structures are not formed in a vacuum, there is intricate feedback between the architecture of a structure, its  
64 residents, and the external environment. Structures are constantly renovated: nest remodeling in social insects  
65 allows colonies to alter gas exchange dynamics<sup>9</sup> and respond to changes in colony size<sup>10</sup>. Thus, there is constant  
66 feedback between a structure and the needs of the individuals that reside in it. Engineers study the constraints  
67 that built structures are subjected to by the physical attributes of the materials used for construction. We argue  
68 that the social activities taking place in these structures should also be considered when designing structures.  
69 Currently, we know very little about how the functional needs of a group influences their built structures and  
70 changes to it over time. Testing the bi-directional relationship between built structures and collective behaviors in  
71 social animals can be as simple as examining the architecture of structures animals build when subjected to  
72 different environmental constraints to facilitate the most effective collective outcomes. Such work with social  
73 animals can rapidly explore a wide array of environments and outcomes, thus expediting our improvement of  
74 human architectural design.

75

76 **Conclusions**

77 Interdisciplinary work on architecture and collective behavior may uncover new biomimicry concepts<sup>11</sup> that will  
78 create synergies among biologists, social scientists, physicists, engineers, and architects. Uncovering general  
79 principles that describe the impact of architecture on collective behaviors has far reaching implications. Most  
80 basically, understanding the effect of structures on the collective behavior of social animals may reveal important  
81 fitness consequences. Furthermore, the scientific understanding of how building architecture influences human  
82 interactions can be used to scaffold collaborations that drive innovation. But there is a greater opportunity for  
83 scientific advances when considering interdisciplinary research that enables studies across multiple species.  
84 Lessons from biology may help formalize the quantification of spaces and uncover architectural features that will  
85 optimize their impact on collaboration. For example, studies on the location of spaces that are used for  
86 communication in social insects (e.g., dancing floor in bees<sup>12</sup>, entrance chamber in ants<sup>13,14</sup>) may inform the  
87 positioning of such features, such as water coolers, which are informal spaces that facilitate the spread of tacit  
88 knowledge, in human buildings. Uncovering how the collective behaviors of social animals are influenced by their  
89 built structures may improve human architectural design and enhance innovations that result from team work by  
90 learning from structures that have been selected by millions of years of evolution. By initiating a cross-disciplinary  
91 conversation we hope to inspire further research on the relationship between architecture and collective behavior.

92

93

94 **BOX 1: Quantifying structures and the social interactions within them**

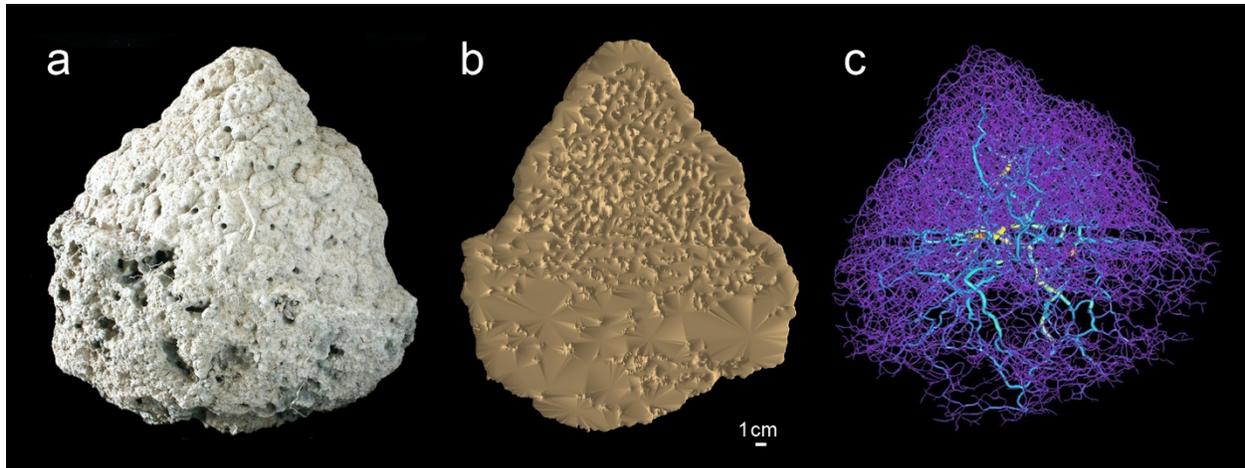
95 Although methods for quantifying structures are essential for examining how structures affect collective outcomes,  
96 we currently lack a diverse quantitative tool-box. Network representations have proven extremely useful for  
97 describing the arrangement of structures in studies of social insects<sup>4,15,16</sup> and humans<sup>6,17,18,19</sup>. However, further  
98 development of algorithms that translate structures into networks, and of relevant network measures, are still  
99 needed to expand this line of research. Furthermore, when chambers or rooms are difficult to define (e.g., in an art

100 gallery), networks may not be suitable. One possible solution is skeletonization which reduces complex 3D  
101 structures to emphasize their geometrical and topological properties (Figure 1, <sup>25</sup>). A glaring methodological gap is  
102 our inability to combine the quantification of both topology and volume of structures into a single variable.  
103 Measuring the volume of structures at different depths <sup>20-22</sup> may provide information on the amount of space that  
104 can be utilized but it holds no information on structure topology. Likewise, an examination of network  
105 representations of structures holds no information on their volume. Finding ways to jointly quantify topology and  
106 volume is an interdisciplinary challenge that calls for cross-disciplinary collaborations to develop tools and  
107 formulas capable of testing the utility and generalizability of such approaches.

108         Once we quantify architectural features, we require methods for examining the movements and  
109 interactions of the occupants of these spaces. Specifically, there is need for methods to quantify the relationship  
110 between movements and the resulting social interactions and various spatial constraints. The use of sensor  
111 technologies, such as tracking devices, provides ample spatial data that can be analyzed in similar ways across  
112 systems. Extracting information on interactions from movement patterns in ants <sup>23</sup> and humans <sup>24</sup> has uncovered  
113 similar interaction patterns within confined spaces. Advances in materials engineering to create devices that are  
114 capable of capturing simultaneously information transfer and movement patterns will allow for studies on both  
115 the form and content of information transfer across different spatial scales and in different species.

116

117 **Figure 1:** An example of the skeletonization of a termite nest (*Trinervitermes geminatus*): (a) a picture of the nest;  
118 (b) a tomographical slice of the nest; and (c) the network of tunnels in the nest in which edges are colored  
119 according to their value of betweenness centrality. The technique used to extract this network is based on <sup>25</sup>.



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