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The impact of architecture on collective behavior

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

Built structures, such as animal nests, serve two overarching purposes: shelter and a space where organisms interact. The former has dominated much of the discussion in the literature ¹. 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 of social animals emerges from interactions ² and collective cognition of humans emerges from communication and coordination ³. 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. An interdisciplinary exchange between behavioral ecologists, evolutionary biologists, cognitive scientists, and architects may 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 behavior.

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

Collective cognition and efficiency

Work on the impact of architecture on collective outcomes has already provided preliminary accounts of how structures influence the efficiency of collective behavior in animals and collective cognition in humans. Biologists have found that the speed at which harvester ants recruit to food increases with the connectivity of nest chambers⁴ and that obstructions near the nest exit of ants facilitate rapid evacuation when in distress⁵. Social scientists have found that the layout of buildings affects scientific collaborations⁶ and innovation⁷. Despite conceptual similarities among these research communities, there has been little, if any, cross-disciplinary communication. Although there are differences among organisms that occupy built structures (e.g., social insects prefer dark spaces and humans prefer light), there are functional similarities, such as the need to coordinate activities and collaborate, which can be extended from one discipline to inform the other. In particular, examining the behavior of animals lends itself to conducting experimental manipulations that are not feasible with human societies. Thus, testing and manipulating social structures and group interactions in social animals, may provide insights on the causative relationships between certain architectural features and collective outcomes that can then be used to improve the efficiency of human societies.

Information processing

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

transmitted. However, being exposed to too much information simultaneously can be overwhelming and cause individuals to shut down and reduce interactions with their surroundings⁸. Thus, structures that segregate individuals (e.g., chambers and tunnels), may reduce stimuli and help filter unnecessary information. Second, certain spatial cues, such as the chemical trails of social insects and road signs in human transportation networks, can aid in the interpretation and use of information. Such cues in the environment can help avoid information overload by externalizing knowledge that can then be used as a scaffold for further information building. Despite the economic implications of such structures (furniture, signs, obstacles etc.) on work productivity in humans, there has been little quantitative research on how spatial layouts and physical artifacts can influence collective information processing. By manipulating spatial signals and physical obstacles to examine their impact on the collective actions of social animals, we can develop new, biologically inspired, means to improve information processing in humans.

Feedback between structure and behavior

Structures are not formed in a vacuum, there is intricate feedback between the architecture of a structure, its residents, and the external environment. Structures are constantly renovated: nest remodeling in social insects allows colonies to alter gas exchange dynamics⁹ and respond to changes in colony size¹⁰. Thus, there is constant feedback between a structure and the needs of the individuals that reside in it. Engineers study the constraints that built structures are subjected to by the physical attributes of the materials used for construction. We argue that the social activities taking place in these structures should also be considered when designing structures. Currently, we know very little about how the functional needs of a group influences their built structures and changes to it over time. Testing the bi-directional relationship between built structures and collective behaviors in social animals can be as simple as examining the architecture of structures animals build when subjected to different environmental constraints to facilitate the most effective collective outcomes. Such work with social animals can rapidly explore a wide array of environments and outcomes, thus expediting our improvement of human architectural design.

Conclusions

Interdisciplinary work on architecture and collective behavior may uncover new biomimicry concepts¹¹ that will create synergies among biologists, social scientists, physicists, engineers, and architects. Uncovering general principles that describe the impact of architecture on collective behaviors has far reaching implications. Most basically, understanding the effect of structures on the collective behavior of social animals may reveal important fitness consequences. Furthermore, the scientific understanding of how building architecture influences human interactions can be used to scaffold collaborations that drive innovation. But there is a greater opportunity for scientific advances when considering interdisciplinary research that enables studies across multiple species. Lessons from biology may help formalize the quantification of spaces and uncover architectural features that will optimize their impact on collaboration. For example, studies on the location of spaces that are used for communication in social insects (e.g., dancing floor in bees¹², entrance chamber in ants^{13,14}) may inform the positioning of such features, such as water coolers, which are informal spaces that facilitate the spread of tacit knowledge, in human buildings. Uncovering how the collective behaviors of social animals are influenced by their built structures may improve human architectural design and enhance innovations that result from team work by learning from structures that have been selected by millions of years of evolution. By initiating a cross-disciplinary conversation we hope to inspire further research on the relationship between architecture and collective behavior.

BOX 1: Quantifying structures and the social interactions within them

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

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

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

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

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