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Swarming bats and the collective soundscape: replication and extension

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Echolocating bats leave caves in dense columns of thousands of individuals, even though each bat's own echoes should be masked by its neighbors' calls. A recent agent-based model by Vanderelst and Peremans (1) shows that collisions can be avoided without separating one's own echoes: each simulated bat turns away from the louder side of the surrounding sound. Its agents, however, spread out more than real bats, fly at a fixed height, and were tested only in flat arenas without height differences. We ran the authors' code with fixed seeds and 15 runs per condition to establish baselines in three arenas and in a condition without other agents' calls and echoes. All published medians fall within the range of our runs, although our typical spacing is tighter (0.72 vs 0.90 m). We will add vertical movement, new arenas, and a cohesion mechanism based on attraction to the collective sound, and examine how cohesion trades off against collision avoidance and exit time.

echolocation | collective behavior | bat swarms | agent-based model | collision avoidance

Significance

The primary goal of the following report is replicating the results Vanderelst and Peremans (1) achieved in their paper describing an agent-based simulation of the behavior exhibited by groups of echolocating bats, more specifically *Tadarida brasiliensis*, when emerging from or entering caves. The paper suggests an alternative solution to the problem of bats navigating their roosts without collisions. The secondary goal is defining extensions for the shortcomings of the paper, like adding vertical movement, more arenas and a cohesion mechanism. This project hopes to further deepen the understanding of group behavior of bat swarms and suggest a refined mechanism for swarm navigation.

1. Introduction

Echolocating bats navigate by emitting calls and listening for the echoes that return from their surroundings, and their auditory systems are highly specialized for this task. In large crowds, however, it becomes difficult for a bat to distinguish its own echoes from the calls and echoes of others, a version of the cocktail party problem.

The problem is most striking in Brazilian free-tailed bats (*Tadarida brasiliensis*), which form some of the largest colonies in the world, with millions of individuals roosting in caves. When emerging, they form a tight, serpentine column at rates of up to tens of thousands of bats per minute (1), and their calls are reflected by the narrow cave entrance as well as by neighboring bats. There is no confirmed explanation of how individuals navigate such crowds, partly because studying the problem directly is technically challenging (2).

Several researchers have addressed this problem with simulations. Beleyur and Goerlitz modeled the sensory input of echolocating bats in large groups and suggest that bats can detect at least their nearest neighbors, which prevents collisions (3). Mazar and Yovel simulated bats finding the exit of a crowded colony using echolocation only, and found that even agents unable to tell objects from other bats can leave the colony, although less often (4).

Vanderelst and Peremans (1) propose that bats do not need to pick out their own echoes at all. Instead, each bat could use the collective soundscape of the swarm: it adds up everything it hears at its left and right ear and turns away from the louder side. In their simulation, groups of agents following this rule fly through branched, curved and widening corridors with few collisions with walls and with each other. Their agents, however, spread out more than real bats, because the mechanism only pushes agents apart and nothing holds the group together. In addition, no field measurements of call rate or flight speed inside caves exist, so the model parameters rest on observations made elsewhere.

This leaves three open questions that motivate our project. First, whether the published results can be reproduced and how robust they are to the model's parameters. Second, how the strategy fares in environments beyond the original arenas, which are all flat, with the entrance and exit at the same height, and cover only a limited range of places where bats occur. Third, whether a cohesion mechanism can keep the swarm together without compromising

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J.G. replicated the results using the available code, M.K. found supporting research for the extensions chosen and A.Z. wrote the report. All authors contributed to the choices of extensions and scope.

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collision avoidance. We first reproduce the main results using the authors' published code (5) and compare them with the reported ranges. We then outline three extensions: vertical movement, additional arenas including sloped and urban-like geometries, and a cohesion mechanism based on the collective sound of the group. We will evaluate each with collisions, distances to walls and to other agents, and exit time. The simulation models one possible mechanism, so our results can show whether the strategy is sufficient, not that real bats use it.

2. Methods

2.1. The original model. We build on the agent-based model of Vanderelst and Peremans (1), in which simulated Brazilian free-tailed bats (*Tadarida brasiliensis*) fly through a corridor in a group. Each run starts with 25 agents placed at random positions and headings in a small starting region. The agents fly at 9 m/s and update their course every 40 ms, which corresponds to a call rate of 25 Hz. Turning is limited to a maximum sideways acceleration of $2g$. In every step, the agents are updated one at a time in a freshly randomized order. A run ends when more than half of the agents have reached the exit. An agent that crosses a wall counts as a collision, is slowed to 1 m/s and turned back toward the middle of the corridor. The corridors are about 5 m wide, and three shapes are used: branched, curved and widening.

Each agent steers using only the overall loudness at its two ears, without separating its own echoes from other sounds. At each ear, the model adds up five kinds of sound: the calls of other agents, the echoes of the agent's own call from other agents and from the walls, and the secondary echoes of other agents' calls reflected from bodies and walls. Since bats do not coordinate their calls, the calls of others arrive at random times. The loudness of each sound follows from the distance and direction of its source and from randomly drawn reflection strengths, and the resulting mixture is passed through a simplified model of the bat's inner ear. The difference between the left and right ear is the interaural level difference (ILD), and the agent turns away from the louder side.

2.2. Replication setup. We ran the authors' published simulation code (5) without modifying the model, so that our baselines come from the original implementation. The code ran under Python 3.11 in an Ubuntu environment on Windows Subsystem for Linux, in a virtual environment with the dependencies pinned in the repository. The head-related transfer function data are precomputed and included in the repository. Step-by-step instructions are in the `SETUP.md` file of our repository.

To obtain baselines that are comparable across all planned extensions, we run every condition from a single driver script. The script fixes the random seed of each run, so that any run can be repeated exactly, and records the same set of measures for every condition. The conditions are the default case in the branched, curved and widened arenas, and the condition without the calls and body echoes of other agents, all with 25 agents. Each condition is run 15 times, as in the original study, and a run is stopped after 300 steps if fewer than half of the agents have reached the exit. The driver saves the measures of each run together with the complete simulation state, so that all tables and figures can be regenerated from the stored files.

We count a collision event as one or more wall crossings that are less than five steps apart. Modes of the distance distributions are estimated with a kernel density estimate. The original analysis scripts are not part of the repository, so our modes may differ slightly from the published ones.

2.3. Planned extensions. We will extend the model in three directions. The first two, vertical movement and additional arenas, bring the simulation closer to real flight conditions. The third, a cohesion mechanism, is our main research extension.

2.3.1. Vertical movement. In the original model, agents steer in the horizontal plane only. We will let them also change their flight height, steering with the elevation dependence of the hearing already present in the model. To keep the vertical motion realistic, we will limit speeds and flight heights using 3D

flight trajectories of bats reconstructed from audio (6) and measurements of free-tailed bats diving toward a cave (7). Neither source matches our setting exactly, since one studied a species that forms smaller groups and the other tracked single bats outside the cave. We will therefore use them as plausible ranges, not as targets. We will evaluate the extension with collisions with the floor and ceiling, the distribution of flight heights, and collisions between agents.

2.3.2. Additional arenas. The original arenas are flat, with the entrance and exit at the same height, and none resembles a built environment. We will add arenas in which the entrance and exit are at different heights and arenas that resemble urban environments, motivated by field observations of gray bats (8). We will also reuse the arena layout and the performance measures of Mazar and Yovel (4), such as exit probability and time to exit. Their agents use a different navigation strategy, whereas ours steer only by the collective soundscape, so we take over their arena and measures but not their navigation. Because bats in cities avoid light (9, 10), a visual cue could later complement the soundscape.

2.3.3. Cohesion mechanism. The authors note that their agents spread out more than real bats, because the acoustic strategy only pushes agents apart (1). To keep the idea that each bat senses only the collective soundscape, we will build the mechanism on the adaptive gravity model of Gorbonos et al. (11), which describes how midges stay together in a swarm. Like our bats, the midges respond only to the collective sound of the group. They are attracted toward the sound, and this attraction weakens when the surroundings become too loud, while a short-range repulsion keeps the group from collapsing. We will transfer both parts to our agents: at low loudness an agent is drawn toward the group, and at high loudness the existing steering turns it away from the louder side. We will measure nearest-neighbor distance, collisions and exit time, and compare the spacing with field measurements of emerging colonies (12). This lets us examine whether staying together and avoiding collisions conflict.

3. Results

We selected the baselines according to the question that each extension poses. The default case in the branched arena is the common reference for all extensions. The curved and widened arenas show how much the measures vary with geometry alone, so that differences in new arenas can be attributed to their design. The condition without the calls and body echoes of other agents shows the spacing that results without acoustic repulsion, which a cohesion mechanism must not collapse to. We report the measures of the original study: collisions per run, run duration, distances to walls and to other agents, and the percentage of steps within 13 cm of a wall or of another agent. Distances and proximity fractions skip the first 50 steps, as in the original analysis. Collisions are counted over all steps, since the original study does not say how it counts them.

Table 1 compares our runs with the published medians. None of the 60 runs reached the step limit. In the default branched arena, the exit time (165 steps), the number of collision events (3) and the proximity to walls and to other agents match the published values closely. The typical distance between agents is smaller than published (mode 0.72 against 0.90 m). Without the calls and body echoes of other agents, the spacing collapses as published (0.31 m), and agents are within 13 cm of another agent in 5.8% of steps (published 4.8%). In the curved and widened arenas our collision medians are higher than published (4 and 3 against 2 and 1, and 3 and 2 after the first 50 steps), but the published values lie within our ranges. The exit time depends on the geometry: the median run lasts 165, 150 and 112 steps in the branched, curved and widened arena.

The same runs give reference values for the extensions. For the cohesion mechanism, the field value of 0.47 m (12) lies between the spacing without other agents (0.31 m) and the default spacing (0.72 m). The integrated level at the ears has a median of 577 in the swarm and 350 without other agents, and the calls of other agents are the loudest input in 60% of steps. These values will set the loudness scale on which attraction fades. For vertical movement, heights are fixed with a standard deviation of 0.28 m, the mean speed of 8.8 m/s is

Table 1. Our runs (median [min, max] over 15 runs) compared with the published medians

Condition	Measure	Ours	Published
Branched, default	Steps until exit	165 [163, 167]	164
	Collision events	3 [1, 6]	3
	Within 13 cm of wall (%)	0.56 [0.21, 4.4]	0.43
	Within 13 cm of bat (%)	0.036 [0, 0.14]	0.03
	Bat–bat distance, mode (m)	0.72 [0.61, 0.92]	0.90
Branched, no others	Bat–bat distance, mode (m)	0.31 [0.18, 0.36]	0.31
Curved, default	Collision events	4 [0, 5]	2
Widened, default	Collision events	3 [0, 5]	1

Published values from (1). Collision events are counted over all steps.

close to the maximum of 9 m/s, and ignoring height would reduce the typical spacing from 0.72 to 0.57 m.

4. Discussion

Our runs reproduce the main behavior of the original model, and the published values lie within the range of our runs, although this is a lenient criterion because collision counts vary widely. The medians agree closely for the exit time, the collisions in the branched arena, the proximity to other agents and the spacing without other agents. They differ for the default spacing, which is tighter than published, and for the collisions in the curved and widened arenas, which are slightly higher. Possible causes are the random seeds and the definitions of collision events and modes, which we cannot test without the authors' analysis scripts. Removing the calls and echoes of other agents shrinks the spacing, supporting the interpretation that these sounds separate the agents (1). It does not show that real bats use this strategy.

The model is a simulation whose parameters rest on observations outside caves, its agents keep a fixed flight height, and it has no cohesion mechanism, which our extensions address. The comparison with field data is only indicative, since the simulated spacing describes flight inside corridors and the field measurements describe emerging colonies. We also used the authors' code and not an independent implementation. In the second milestone we will implement the extensions and run them against these baselines, and in the third we will analyze the results, vary the main parameters to test their robustness, and finalize the report.

Data, Materials, and Software Availability. The simulation code used in this study is the one published by Vanderelst and Peremans (5). Our driver script, setup instructions and the summary table of all runs are available at https://github.com/aleksandrazec/Swarming-bats-and-the-collective-soundscape.

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