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Dynamics and stability of milling behaviour under perturbation

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Abstract: Collective motion, such as flocking in birds or milling in fish, provides ecological advantages including predator avoidance and enhanced foraging efficiency. Mills, a common configuration of collective motion, provide an opportunity to study how such structures emerge, persist, and collapse under stress impetus.

We sought to understand under what conditions mills are maintained, and how perturbation might affect the stability, or ability to recapitulate the original milling behaviour, under conditions of perturbation, reminiscent of external cues in the real world, such as predation and topology change. We constructed mills by distributing individuals within a toroidal region, varying density (via manipulation of the inner and outer radii) and initial angular momentum (which measures the agreement in the sense of rotation of group members about the group centre). Perturbations were introduced by periodically randomising velocities of increasing proportions of individuals, up to complete disruption.

Our results showed that increasing the area of the initial torus increased the loss of angular momentum, and as such, milling behaviour, and the number of simulations able to recover the milling phenotype was less. Furthermore, where stable mills formed following simulation start, an increase in the proportion of individuals perturbed led to greater disturbance in mills and generally decreased the number of simulations able to recapitulate the topology.

We noted that, in stable mills, angular momentum and density consistently approached, and remained about, 0.9 and 0.2 (individuals per unit area/per unit volume), respectively. Consequently, we incorporated these observations to produce three sets of simulations, with angular momentum thresheld about 0.2, each with densities of approximately 0.01, 0.2 and 1. We found that induced mills, independent of angular momentum, could only be maintained when the density of the initial mill ~0.2, suggesting that collective structures, such as mills, are not only emergent but also contingent upon specific parameter regimes including group density. This work offers mechanistic insight into how real-world groups maintain cohesion under ecological disturbance.

Keywords: *Collective Motion, Milling, Density, Angular Momentum*