One ring to rule them all: tuning bacteria collective motion via geometric confinement

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Abstract
Suspensions of swimming bacteria are known to self-organize into turbulent-like flows for sufficiently high density and nutrients concentration. This spectacular example of collective behavior, on which the survival of the colony itself is believed to rely, appears however impossible to control. In a recent experimental and computational study, Wioland et al (2016 New J. Phys. 18 075002) have demonstrated that the collective motion of *B. subtilis* can be in fact selectively tuned by confining the system into a ring-shaped channel.

Collective motion is possibly the most common feature among groups of living organisms apart from life itself. It occurs within a single cell, when the building blocks of the cytoskeleton self-organize into the powerful motility machinery [1], as well as in bacteria [2], algae [3], sperm [4], insects [5], fish [6], birds [7] and, in general, in nearly any group of individuals endowed with the ability to move and sense. This spectacular example of robustness has inspired science and technology in a two-fold way: on one hand scientists have focused their efforts in understanding the origin of a collective behavior found in systems of such an astonishing diversity [8]; on the other hand, technologists have envisioned the possibility of implementing this form of organization that spontaneously arises in living systems to construct swarms of devices that can work independently and yet collectively towards a common goal [9].

In the minimalistic world of bacteria, collective motion is believed to be functional to the survival of the colony: cells moving together efficiently migrate toward regions rich in nutrients [10] or build fruiting bodies when resources are scarce [11]. These examples of self-organization are generally triggered by environmental stimuli, these being in the form of chemical gradients, mechanical cues or geometrical constraints.

For the past two decades, the conceptual framework of *active matter* (i.e. any physical systems whose constituents can autonomously move and generate forces), acted as a linchpin to decipher the emergence of collective motion is systems of self-propelled building blocks [8]. Yet, our understanding of the role of the environment in collective motion, and in particular the effect of geometrical confinement, is still in its infancy [5, 12, 13] and the questions outnumber the answers by far. The recent paper by Wioland et al [14] addresses this challenge through a creative combination of *in vitro* and *in silico* experiments.

The experimental setup consists of an array of ring-shaped ‘racetracks’, about one millimeter in length and having various micron-sized widths (figure 1(a)). Hundreds of thousands of motile *B. subtilis* cells were injected in this circuit and let free to race, while the experimenters were carefully tracking their velocity and orientation. Depending on the width of the confining channel, this active bacterial suspension was observed to self-organize into three well distinct dynamical behaviors. In wide channels (i.e. >70 \( \mu \)m), bacterial motion gives rise to a turbulent-like flow (figure 1(b)), in spite of the undisputed predominance of dissipation over inertia at the microscopic scale [15]. Decreasing the channel width below 70 \( \mu \)m has the effect of taming the chaos, by transforming the turbulent flow into a regular vortex street coherently circulating into the racetracks, either clockwise or counterclockwise (figure 1(c)). When the channel width is decreased even further (i.e. <40 \( \mu \)m), the flow becomes fully laminar and the velocity field exhibits the classic parabolic profile of channel flows (figure 1(d)).
To get insight into this well reproducible sequence of flow behaviors, Wioland et al. have further considered a computational model consisting of elliptical swimmers confined into a two-dimensional channel and interacting with each other and with the confining walls both sterically and hydrodynamically. Their numerical simulations show that, when the system is sufficiently dense, a layer of orientationally ordered bacteria forms along the walls. In the absence of hydrodynamic interactions, however, this spatial organization remains confined at the boundary, while the bacteria in the bulk of the channel frantically move back and forth without coherence. Switching on hydrodynamics provides the bacteria with a vehicle to propagate their state of order further in space. The coherent flow generated by the bacteria trapped at the boundary now propagates in the bulk and, for narrow enough channels, gives rise to a self-organized 'conveyor belt' that transports the bacteria in the middle of the channel, leading to stable circulation.

The work by Wioland et al. represents a significant step toward understanding the role of geometrical confinement in active matter. While the existence of a low Reynolds number turbulence in bacterial suspensions, as well as other active fluids [16–19], is now firmly established, this article provides the first experimental observation of the crossover from laminar to turbulent flow in active fluids and highlights the role of the confinement length scale as a control parameter for collective behavior. This latter finding further supports the (up to now only theoretical) idea that active fluids endowed of internal orientational order can be found in three dynamical states, laminar, periodic or chaotic flow, depending on the ratio between system size (i.e. the confinement length scale in this case) and the inherent length scale resulting from the competition between active forces, that tend to disorder the system, and passive restoring forces (viscous or elastic) [18].

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Figure 1. Wioland et al. experimental work demonstrates that the flow behavior of an active bacterial suspension can be controlled by tuning the length scale at which bacteria are confined. (a) Typical ring-shaped racetrack used in the experiments. Tracks are about 1 mm in length and have various widths in the range 35–90 μm. (b) In wide channels, the system exhibits low Reynolds number turbulence. (c) Upon decreasing the channel width, the flow transforms into a regular vortex street coherently circulating along the racetrack. (d) For very narrow channels, the flow has the classic parabolic profile of laminar channel flows. Adapted from [14].
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