

Intrinsic chirality reshapes collective states in perception-driven active matter

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Biological systems often combine intrinsic rotation with directional sensing and nonreciprocal interactions. However, the collective consequences of these combinations are poorly understood. Here, we extend a previously studied model of active Brownian particles with vision-mediated steering, polar alignment, and steric repulsion by adding intrinsic chirality, and examine how the additional rotational timescale introduced by intrinsic chirality reorganizes the resulting collective dynamics. We vary the alignment-to-vision maneuverability ratio, the vision angle, and the chirality to obtain dynamical state diagrams containing compact spinning clusters, vortices, ripple loops, wormlike swarms, and mobile rotary clusters. Intrinsic chirality alters the balance between vision-mediated cohesion and velocity alignment, giving rise to the observed rotary behavior. Large chirality suppresses collective organization, while moderate-to-low chirality stabilizes rotating and translating clusters. At moderate chirality, the model exhibits a ripple-loop morphology. We use both structural and dynamical measures like polarization, orientational correlations, solid-body spin, and mean squared displacement to distinguish the different regimes and the pathways between them.

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I. INTRODUCTION

Over the past few decades, self-propelled particles have gained significant attention as minimal models for investigating collective, nonequilibrium dynamics in both synthetic and biological systems. Among these, active Brownian particles (ABPs)—isotropic particles with constant self-propulsion and stochastic rotational diffusion—provide a canonical framework for exploring emergent behaviors such as clustering and motility-induced phase separation. In the absence of rotational noise or other symmetry-breaking effects, isotropic ABPs maintain a fixed orientation and move along straight-line trajectories. Thus, self-propulsion itself gives a polarity to the particles [1]. Presence of rotational diffusion progressively randomizes their direction, resulting in a persistent random walk. At the collective scale, such active units can exhibit coordinated motion and self-organized group formation without central control, as routinely observed in ethological systems [2,3]. These phenomena manifest as swarms, flocks, and herds, and constitute hallmark features of living systems across scales—from bacterial biofilms to schools of fish, flocks of birds, and herds of mammals [4–7].

Chiral motion arises when microswimmers experience an intrinsic torque, leading to circular or helical trajectories rather than purely linear propulsion. Such chirality can

originate from structural asymmetries [8,9], hydrodynamic interactions with boundaries in systems such as bacteria and sperm cells [10–16], or more generally from obstacle interactions and time-delayed dynamics [17,18]. Similar behavior is observed in synthetic realizations, including self-phoretic swimmers and artificial cells [19,20], indicating that intrinsic rotation is a generic feature of active matter.

In systems with alignment interactions, chirality has been shown to qualitatively reshape collective dynamics. Within Vicsek-type models [21], the onset of flocking remains largely unchanged, but intrinsic rotation leads to the emergence of structures such as microflocks, vortices, and rotating polar packets [22–24]. These states often reflect a competition between alignment-induced ordering and rotational decorrelation, resulting in finite-sized clusters, synchronization phenomena [25], and chiral pattern formation [26]. Even in the presence of excluded-volume interactions or attractions, chirality continues to promote rotating and vortexlike structures [27,28], highlighting its role as a key ingredient controlling collective organization.

A complementary route to collective behavior arises from nonisotropic, perception-based interactions. In such systems, particles respond selectively to neighbors within a restricted field of view, leading to inherently nonreciprocal interactions. Vision-based models, even in the absence of explicit alignment, can generate aggregates, milling states, and nematic order [29,30], while additional ingredients such as adaptive motility or misaligned perception give rise to swirling and circulating collective motion [31–34]. Extensions to intelligent active Brownian particles, which combine vision-based steering with alignment and steric interactions, exhibit a broad spectrum of morphologies ranging from wormlike swarms to compact aggregates [35,36]. More generally, perception-driven nonreciprocal interactions provide a robust

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mechanism for generating complex nonequilibrium structures [37,38].

Despite these advances, the combined effect of intrinsic chirality and perception-driven interactions remains largely unexplored. Previous studies of vision-cone interactions have primarily focused on particles with linear self-propulsion, whereas studies of chiral active matter have generally employed isotropic interaction rules. Consequently, it remains unclear how the persistent turning tendency associated with chirality modifies the anisotropic and nonreciprocal interactions introduced by a finite vision cone. This interplay is not simply additive: Chirality continuously rotates the direction of self-propulsion, while perception restricts interactions to a dynamically evolving angular sector, leading to a competition between intrinsic rotation, directional sensing, alignment, and steric interactions. As we show below, this competition gives rise to qualitatively different collective organization and phase behavior compared to systems in which either ingredient acts alone, including the emergence of vortex, ripple, and rotary states in parameter regimes where the corresponding nonchiral vision-cone model does not exhibit them. Our results demonstrate that intrinsic turning bias fundamentally reshapes perception-mediated collective dynamics rather than merely introducing a small perturbation to an existing model.

Therefore, we extend a vision-based model of interacting active Brownian particles with alignment interactions by incorporating intrinsic chirality. By varying the vision angle, alignment strength, and intrinsic turning rate, we systematically investigate how these competing ingredients reorganize collective dynamics and the resulting nonequilibrium phase behavior.

II. MODEL

We consider a system of N chiral active Brownian particles, with positions denoted by $\mathbf{r}_i(t)$ ($i = 1, 2, \dots, N$) at time t . Each particle self-propels at a speed $v_0 = F^a/\gamma$ along the propulsion direction $\hat{\mathbf{e}}_i(t) = (\cos \varphi_i, \sin \varphi_i)^T$, where φ_i is the polar angle of the i th particle and F^a —identical for all particles—is the active force responsible for the propulsion. The dynamics of the particles are described by the overdamped Langevin equation,

$$\dot{\mathbf{r}}_i(t) = v_0 \hat{\mathbf{e}}_i + \frac{1}{\gamma} \mathbf{F}_i(\{\mathbf{r}\}) + \frac{1}{\gamma} \boldsymbol{\zeta}_i(t). \quad (1)$$

Here, γ is the translational friction coefficient, and $\mathbf{F}_i = -\partial U(\mathbf{r})/\partial \mathbf{r}_i$ is the interparticle force arising from steric or excluded-volume interactions, which is taken to be the Weeks-Chandler-Andersen potential:

$$U(r) = \begin{cases} 4\epsilon \left[\left(\frac{\sigma}{r} \right)^{12} - \left(\frac{\sigma}{r} \right)^6 \right] + \epsilon, & r \leq 2^{1/6} \sigma, \\ 0, & \text{otherwise,} \end{cases}$$

where σ is the particle's diameter and ϵ is the depth of the potential. The term $\boldsymbol{\zeta}_i$ represents stochastic forces, modeled as Gaussian white noise, with

$$\langle \boldsymbol{\zeta}_i(t) \rangle = 0, \quad \langle \boldsymbol{\zeta}_i(t) \cdot \boldsymbol{\zeta}_j(t') \rangle = 4\gamma k_B T \delta_{ij} \delta(t - t'),$$

T being the temperature and k_B is the Boltzmann constant.

The orientation dynamics of the i th particle, incorporating visual-perception-based steering, polar alignment interac-

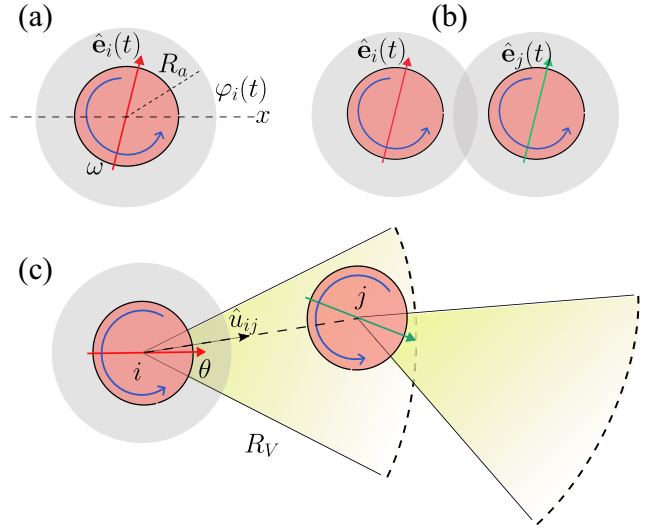


FIG. 1. (a) The alignment zone (shaded in gray) of radius R_a , the rotation direction (curved blue arrow), and the self-propulsion direction (red arrow) of a particle i . φ_i is the angle that $\hat{\mathbf{e}}_i$ makes with the x axis. (b) Two particles tend to align their orientation direction if their alignment zones overlap. (c) j th particle falls within the vision cone of the i th particle. So the i th one orients its propulsion direction toward the j th one. θ is the half-opening angle of the vision cone, R_V is the maximum vision range, and $\hat{\mathbf{u}}_{ij}$ is the unit vector from i th to j th particle.

tions, and an intrinsic chirality, is given by [35,39]

$$\begin{aligned} \dot{\varphi}_i = & \omega_i + \frac{\Omega_v}{N_{c,i}} \sum_{j \in \text{VC}} e^{-r_{ij}/R_0} \sin(\phi_{ij} - \varphi_i) \\ & + \frac{\Omega_a}{N_{a,i}} \sum_{j \in \text{PA}} \sin(\varphi_j - \varphi_i) + \Lambda_i(t), \end{aligned} \quad (2)$$

where the first term represents the angular velocity due to intrinsic chirality, the second term corresponds to vision-based torque, the third term to polar-alignment torque, and the final term to rotational noise. The noise is Gaussian and Markovian, satisfying $\langle \Lambda_i(t) \rangle = 0$ and $\langle \Lambda_i(t) \Lambda_j(t') \rangle = 2D_r \delta_{ij} \delta(t - t')$, and gives rise to rotational diffusion. The relative importance of these torque contributions can be conveniently characterized in terms of their associated reorientation timescales.

The vision-perception-based steering torque acts as a cohesive torque. ϕ_{ij} is the angle between $\hat{\mathbf{u}}_{ij} = (\cos \phi_{ij}, \sin \phi_{ij})^T$ and the x axis, where $\mathbf{u}_{ij} = \mathbf{r}_j - \mathbf{r}_i$ is the vector from particle i to j (Fig. 1), and each chiral active Brownian particle has a finite range of visual perception, sensing only particles within a forward-facing vision cone (VC). Ω_v is the visual maneuverability, determining the timescale of the torque responsible for reorienting it toward the neighbors it perceived, and the normalization factor is

$$N_{c,i} = \sum_{j \in \text{VC}} e^{-r_{ij}/R_0}. \quad (3)$$

The VC has a half-opening angle θ and range R_V . A particle j lies within i 's VC if

$$\hat{\mathbf{u}}_{ij} \cdot \mathbf{e}_i \geq \cos \theta, \quad |\mathbf{r}_j - \mathbf{r}_i| \leq R_V. \quad (4)$$

TABLE I. Glossary of symbols and simulation parameters used in the text, along with typical values.

Parameter	Description	Value (unit)
σ	Particle diameter	1.0
$k_B T$	Energy scale	1.0
Φ	Packing fraction	0.00785
D_r	Rotational diffusion coefficient	0.08
D_T	Translational diffusion coefficient	$0.125 \sigma^2 D_r$
Pe	Péclet number	10–70
ω	Chiral angular velocity	$0.125\text{--}25 D_r$
θ	Vision angle	$\pi/6\text{--}\pi$
Ω_v	Vision maneuverability	$12.5 D_r$
Ω_a	Alignment maneuverability	$0.1\Omega_v\text{--}20\Omega_v$
R_0	Effective vision range (crowded)	1.5σ
R_V	Vision range	$4R_0$
R_a	Polar alignment radius	2σ

Instead of an abrupt cutoff [29], we use an exponential distance dependence [39]. The VC geometry and the normalization factor $N_{c,i}$ explicitly break action-reaction symmetry—thereby leading to nonreciprocal interactions—while the weight e^{-r_{ij}/R_0} biases interactions toward nearby neighbors. As a result, the *effective* interaction range is set by R_0 , with R_V acting only as a geometric cutoff.

For the polar-alignment torque, Ω_a denotes the alignment strength and $N_{a,i}$ the number of neighbors within the interaction range R_a ($|\mathbf{r}_i - \mathbf{r}_j| \leq R_a$). Alignment and vision contribute independently: A neighbor within R_a contributes to M_i^a , while one inside the VC contributes to M_i^v . If both conditions are satisfied, the contributions add, yielding $M_i = M_i^a + M_i^v$.

Further, the activity of a chiral active Brownian particle is characterized by the dimensionless Péclet number

$$\text{Pe} = \frac{\sigma v_0}{D_T}, \quad (5)$$

where $D_T = k_B T / \gamma$ is the translational diffusion coefficient.

Here, we consider a relatively large set of independent control parameters, as presented in Table I, namely, the chirality ω , the Péclet number Pe, the packing fraction Φ , the alignment and vision maneuverabilities Ω_a and Ω_v , the vision angle θ , the vision range R_0 , and the polar-alignment radius R_a . To make analysis simpler, only the dimensionless Pe, the ratios Ω_a/Ω_v , and ω/D_r are relevant in the following analysis.

Following Ref. [35], we restrict our study to the regime $\Omega_a/\Omega_v \in [0.1, 20]$ and vision angles $\theta \in [\pi/6, \pi]$, where the key characteristics of the system are most clearly manifested. The chosen vision range corresponds to realistic scenarios and, importantly, enables us to isolate intrinsic chirality as the only additional ingredient relative to the reference system. Consequently, any observed changes in collective behavior can be directly attributed to the presence of chirality.

III. PARAMETERS AND SIMULATION DETAILS

We performed two-dimensional overdamped Brownian dynamics simulations in LAMMPS [41]. Lengths are expressed in units of σ and energies in units of $k_B T$. The interac-

tion strength is chosen as $\epsilon = (1 + \text{Pe})k_B T$, ensuring robust excluded-volume interactions even at high activity [39]. The translational friction coefficient is $\gamma = 100$, and the rotational diffusion coefficient is $D_r = 0.08$, which defines the characteristic timescale $\tau = 1/D_r$.

The packing fraction is $\Phi = \pi \sigma^2 N / (4L^2)$, where L is the box length; periodic boundaries are applied in both directions. We use an integration time step $\Delta t = 5 \times 10^{-4}$; the system is evolved for 2×10^7 steps to reach a nonequilibrium steady state, and data are subsequently collected over 3×10^7 time steps. Unless stated otherwise, simulations involve $N = 625$ particles at $\Phi = 0.00785$, below the threshold for motility-induced phase separation [42].

The vision range is $R_0 = 1.5\sigma$, with $R_V = 4R_0$, and the alignment radius is $R_a = 2\sigma$. The vision maneuverability Ω_v/D_r is held constant at 12.5, while the ratio Ω_a/Ω_v is modulated by varying the alignment strength Ω_a . This allows us to probe the crossover from vision-dominated to alignment-dominated dynamics.

Initial conditions

The initial configuration consists of particles arranged on a square lattice at the center of the simulation box, with a lattice spacing of σ . Alternatively, the system can be initialized in a dilute, gaslike state, where particles are positioned far apart from each other. In this case, parameters corresponding to single-aggregate states become diffusion-limited: The system first forms several smaller aggregates, which then gradually coalesce, resulting in a slower formation of a single aggregate. This behavior has also been reported in Ref. [39].

IV. RESULTS

A. State diagram I: Dependence on chirality

Since intrinsic chirality modifies the rotational dynamics of the particles, we systematically vary the angular velocity ω from small to large values at a fixed Péclet number, $\text{Pe} = 10$, and vision angle $\theta = \pi/3$. To characterize the resulting dynamics, we explore the parameter space spanned by the ratio of alignment to vision maneuverability, Ω_a/Ω_v , and the reduced chirality, ω/D_r . Representative snapshots of the distinct collective states (for $\omega/D_r = 0.25$) are provided in Fig. 2 for reference, with additional examples shown in the Movies of the Supplemental Material [40]. Using the clustering coefficient as a diagnostic, we construct the state diagram shown in Fig. 3. The boundaries between different regimes should be interpreted as gradual crossovers rather than sharp thermodynamic phase transitions. The clustering coefficient, defined as s_l/N , where s_l denotes the size of the largest cluster and N is the total number of particles, quantifies the propensity of the system to form clusters. Typically, dilute regimes correspond to $s_l/N < 0.1$, whereas strongly clustered states satisfy $s_l/N \geq 0.2$.

In this subsection, we provide a brief overview of the observed collective states and their evolution with chirality. A more detailed analysis of these states is presented in the following subsection, where we examine the $\theta\text{--}\Omega_a/\Omega_v$ state diagram in detail.

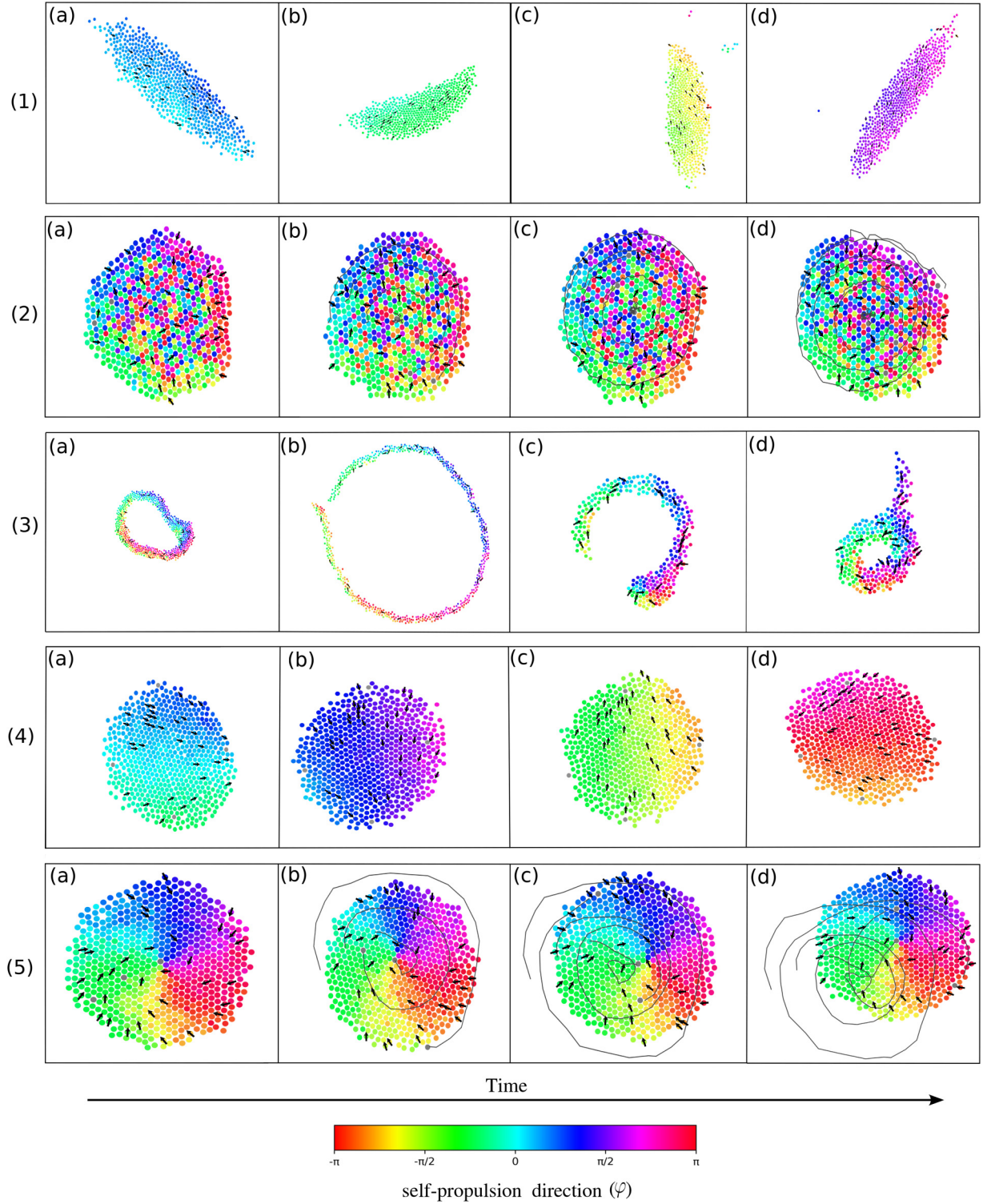


FIG. 2. Snapshots of representative collective dynamical states. Panels (1)–(5) show (1) *wormlike cluster* ($\Omega_a/\Omega_v : 20, \theta : \pi/3$), (2) *spinners* ($0.1, \pi$), (3) *ripple* ($0.5, \pi/4$), (4) *rotating cluster* ($20, \pi$), and (5) *vortex* ($4, \pi/2$) structures. Particle colors represent their orientation, with the color bar below showing how orientation angles are mapped to different colors. Small black arrows provide additional directional cues. In panel (3), sublabels mark the following: (a) a ripple loop encompassing all particles, (b) loop breaking on the left, (c) an enlarged view of particles reaccumulating after the break, and (d) formation of a new ripple. In panels (2) and (5), black curved lines trace the trajectories of three highlighted particles (gray), showing that the *dense spinning aggregates* remain nearly stationary, whereas the *vortex* both rotates and translates as a whole. Also see the Movies in the Supplemental Material [40].

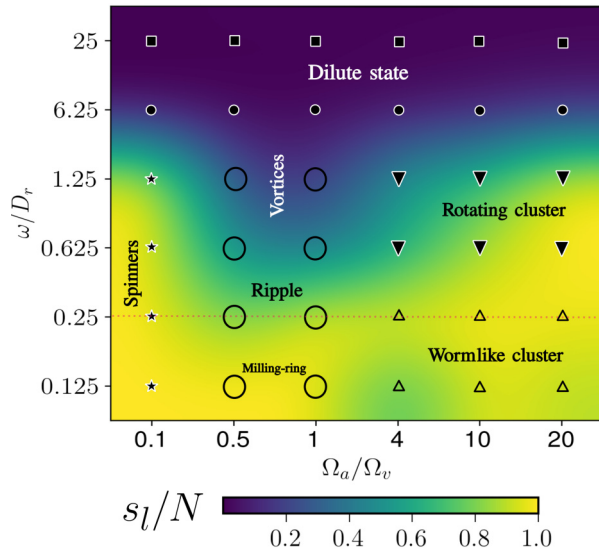


FIG. 3. State diagram of the observed collective states for $Pe = 10$ at a fixed vision angle of $\theta = \pi/3$. The ratio of alignment to vision maneuverability, Ω_a/Ω_v , is varied along the x axis, while the reduced chirality, ω/D_r , is varied along the y axis. The background color code corresponds to time-averaged clustering coefficient, defined as s_l/N , where s_l is the size of the largest cluster and N is the total number of particles. Stars: spinners; filled squares and circles: dilute states; empty circles: vortices, ripples, and milling rings; empty triangles: worms; and inverted filled triangles: rotary clusters. The dashed red horizontal line corresponding to $\omega/D_r = 0.25$ indicates the parameter regime that is the focus of subsequent analysis.

Pursuit-dominated regime: This regime is characterized by pursuit-dominated interactions, i.e., $\Omega_a \leq \Omega_v$. When the visual maneuverability is the dominant interaction, we find, up to a reduced chirality of $\omega/D_r \sim 1.25$ (Fig. 3), a single jammed state in which angular velocities propagate throughout the cluster, producing collective solid-body-like spinning. As shown in Fig. 2 [panel (2)], the curved tracer lines confirm that the entire cluster undergoes coherent spinning despite the absence of global orientational order; we therefore refer to this state as *spinning* rather than rotation. Beyond $\omega/D_r \sim 1.25$, the structural integrity of the cluster rapidly deteriorates, and the system gradually evolves into a completely dilute state.

With a slight increase in the alignment strength, the initially jammed interior reorganizes into a coherent vortexlike flow with particles remaining locally aligned [Fig. 2, panel (5)]. The chirality then determines whether this restructuring proceeds directly or through intermediate ripplelike states. When vision-mediated maneuverability dominates, particles within the vortex core align while rotating and acquire a net outward orientation, promoting radial expansion of the compact vortex. Owing to their wavelike morphology, we refer to these expanding structures as *ripples* [Fig. 2, panel (3)]. Their orientational field exhibits a characteristic spatial organization, with particles tilted outward near the inner boundary, inward near the outer boundary, and tangential alignment in between. At very low chirality, the radial expansion saturates after a modest increase in size, resulting in stable milling rings. With increasing chirality, these evolve into continuously expanding ripple states, indicating that chirality plays a key

role in sustaining the expansion dynamics. At still higher chirality, the clusters begin to fragment, producing multiple small but compact vortices (corresponding to the dip in the color scale), which suggests that ripple formation requires a sufficiently large number of interacting particles. Finally, for sufficiently large chirality, the clusters completely disintegrate and the system becomes dilute.

Alignment-dominated regime: When alignment moderately exceeds visual cohesion, *wormlike aggregates* dominate at very low chirality. These structures, well known in cohesive, polar-aligning active Brownian systems, emerge as leader—follower swarms in which a transient leader guides the group while leadership is continuously exchanged [Fig. 2, panel (1); see Movie M1 in the Supplemental Material [40]]. Their appearance also demonstrates the consistency of our model with the behavior of systems driven purely by linear self-propulsion. As the chirality increases, the wormlike state gives way to *rotary clusters*, which exhibit strong global polarization combined with coherent collective rotation induced by the intrinsic particle chirality [Fig. 2, panel (4)]. Unlike jammed spinners, which suppress translation, rotary clusters remain mobile and display collective orbital motion. A further increase in chirality destabilizes these clusters, eventually leading to a dilute state.

As is clear from Fig. 3, for sufficiently large chirality, the system always evolves to a dilute state, irrespective of the maneuverability ratio, Ω_a/Ω_v . As chirality increases, the rotational timescale, $1/\omega$, becomes shorter than the alignment and visual-cohesion timescales, preventing particles from maintaining the interactions needed for stable clusters. At $\omega/D_r = 6.25$, only weak, transient patches remain, motivating the use of alternative markers in the state diagram.

B. State diagram II: Dependence on vision angle

Having established the overall evolution of the system with chirality in the preceding subsection, we now focus on the representative parameter set $\omega/D_r = 0.25$ and $Pe = 10$, where the richest variety of stable collective states is observed. This provides an ideal setting for examining how the vision angle shapes the structure and dynamics of these states. Accordingly, we vary the vision angle, θ , from $\pi/6$ to its maximum value, π . (For completeness, the case of higher persistence, $Pe = 70$, is briefly discussed in the Supplemental Material [40]).

To characterize the resulting dynamics, we explore the parameter space spanned by the ratio of alignment to vision maneuverability, Ω_a/Ω_v . Unlike the ω/D_r – Ω_a/Ω_v state diagram, this parameter regime is dominated by cohesive clustered states. We therefore construct a second state diagram in which the solid-body spin (SBS) (Sec. IV D 2) is represented as a heatmap to highlight the degree of collective rotation. The resulting diagram is shown in Fig. 4. As in the previous state diagram, the boundaries between the different regimes should be interpreted as smooth crossovers rather than sharp transitions.

$\Omega_a < \Omega_v$: For large vision angles, each particle interacts with a larger number of neighbors. Under weak polar alignment, these interactions stabilize the spinning state discussed above [Fig. 2, panel (2)]. As the vision angle decreases, the

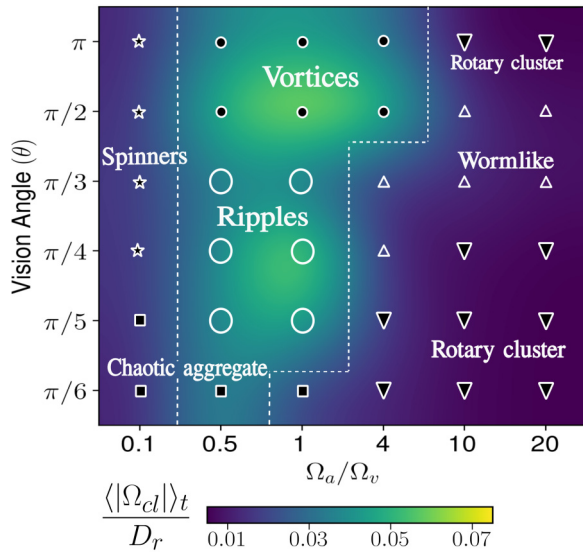


FIG. 4. State diagram of the observed collective states for $Pe = 10$ at a fixed chirality of $\omega/D_r = 0.25$. The ratio of alignment to vision maneuverability, Ω_a/Ω_v , is varied along the x axis, while the vision cone, θ , is varied along the y axis. The heatmap corresponds to the value of dimensionless time-averaged *solid-body spin* of a cluster $\langle |\Omega_{cl}| \rangle_t / D_r$, which is detailed in the text (Sec. IV D 2). The average is taken over time interval relevant for the state under consideration, e.g., a spinner undergoes few complete spins, a ripple loop undergoes two or more complete rotations, etc. Stars: spinners, filled squares: chaotic aggregates, filled circles: vortices, empty circles: ripples, empty triangles: worms, and inverted filled triangles: rotary clusters. The dashed lines further separates the observed states based on their SBS values, which is further elaborated in the text.

number of interacting neighbors is reduced, leading to a loss of cohesion and the emergence of irregular, shape-changing aggregates. Consequently, collective spinning is suppressed, since efficient transmission of angular velocity requires a compact structure. Similar nonrotating, droplike condensates without internal ordering have been reported in vision-cone-based active systems with delayed interactions [43], while qualitatively similar swirling states have been observed in related active matter systems [32].

$\Omega_a \simeq \Omega_v$: As the alignment strength increases, the jammed spinning state reorganizes into vortexlike flows. The vision angle determines whether this restructuring proceeds directly or through intermediate ripplelike states.

Axisymmetric vortex states are commonly observed in chiral active systems, including models with alignment and rotational disorder, dense chiral ABPs, and experiments on bacterial colonies, colloidal rollers, and sperm layers [8,11,24,25,44–46]. Consistent with previous studies, we observe a reversal between the intrinsic particle chirality and the direction of collective rotation: vortices—including ripples and milling rings—and spinning clusters rotate opposite to the single-particle chiral motion, whereas rotary clusters translate in the same sense as the intrinsic chirality [28,44,47] (see Movies M3–M5 and M7 in the Supplemental Material [40]).

Collective chirality reversal has been reported even in the absence of explicit alignment interactions, where vortexlike domains emerge within larger clusters [44]. A continuum

model with alignment interactions likewise exhibits chirality reversal through the coexistence of a compact rotating cluster and a dilute gaseous background [47]. In another study, explicit attractive interactions produce compact vortex clusters that undergo spontaneous reversals of their rotational direction, unlike the persistent rotation observed here [28]. Although the microscopic interactions differ, the vision-mediated interactions in our model similarly stabilize cohesive rotating clusters, giving rise to qualitatively similar vortex structures.

Milling-ring states have been reported in systems with vision-cone interactions, alignment, and delayed communication, where their stability depends on the field of view and system size [35,48–51]. Similar closed-loop structures also arise in stochastic acceleration models [52]. Unlike these earlier mechanisms, however, both the ripple and milling-ring states in our system emerge through the radial expansion of an initially compact vortex. Their formation mechanisms and internal structures are compared below.

The vision angle plays a central role in determining the stability of these expanding states. At large vision angles, interactions with many neighbors disrupt the leader-follower organization required to sustain ripple expansion, promoting fragmentation into smaller vortices. As the vision angle is reduced, leader-follower dynamics are progressively restored, stabilizing the ripple loops until cohesion is eventually lost at very small vision angles. In most cases, the radial expansion is not sustained indefinitely: Rotational diffusion gradually disrupts the circumferential coherence of the loop, leading to repeated cycles of breakup and reformation [Fig. 2 (3b)]. Under suitable conditions, however, the expansion saturates at a finite radius, producing long-lived milling-ring states, most prominently for $\Omega_a/\Omega_v = 1$ and $\theta = \pi/2$ (Fig. 4). When alignment becomes sufficiently dominant at large vision angles, the outward expansion is suppressed and the system relaxes into a single compact vortex.

$\Omega_a > \Omega_v$: When alignment moderately exceeds visual cohesion, the system undergoes a sequence of transitions—from vortex to wormlike aggregates and eventually to rotary clusters—as the vision angle decreases. Consistent with earlier studies [39,53], the internal organization of the worms remain highly dynamic. At sufficiently small vision angles, the reduced inward forcing from edge particles destabilizes the wormlike structure, giving rise to loosely bound rotary clusters.

States similar to the rotary clusters—often referred to as rotating polar packets [24,25] or microflocks [22]—have been reported in chiral aligning systems. Reference [24] showed that a homogeneous orientationally ordered (polar liquid) state is generically unstable to arbitrarily small chirality disorder in the thermodynamic limit ($L \rightarrow \infty$). This instability leads to the emergence of polar vortices or rotating packets, suggesting that the steady state is intrinsically inhomogeneous. This perspective differs from the activity-induced synchronization scenario, observed in systems with distributed intrinsic frequencies, as proposed in Ref. [23].

For stronger alignment, the vortex interior becomes fully ordered, resulting in rotary clusters at large vision angles. At intermediate vision angles, wormlike states reappear, whereas

TABLE II. Short definition of the states.

State	Definition
Spinners	Solid-body-like spinning motion ($SBS \approx 0.015$) without polar order
Vortices	Solid-body-like spinning motion ($SBS \gtrsim 0.025$ at onset) with patches of aligned particles
Ripples	Vortexlike, but turns to a gradually expanding ringlike morphology; breaks eventually
Worms	Leader-follower-like swarming
Rotating clusters	Globally polarized clusters showing orbitinglike motion

at small vision angles the system again forms rotary clusters, indicating reentrant behavior.

In Fig. 4, the color scale distinguishes the strongly spinning vortex, ripple, and milling-ring states from the remaining collective states. Since spinning clusters exhibit comparatively weak solid-body spin, they appear similar in color to wormlike clusters, rotary clusters, and disordered aggregates. The dashed lines broadly classify the states according to their SBS and are intended only as guides to the eye. Compact vortices, milling rings, and ripples predominantly lie within the range $0.025 \lesssim \langle |\Omega_{cl}| \rangle / D_r \lesssim 0.075$, well separated from the remaining states. Spinning clusters form an intermediate group at $\langle |\Omega_{cl}| \rangle / D_r \approx 0.015$, while wormlike and rotary clusters exhibit the weakest solid-body spin, $\lesssim 0.015$. Although spinners and rotary clusters both fall near or below 0.015, the two are distinguished not by SBS magnitude alone but by the presence (rotary) or absence (spinner) of global polar order, as summarized in Table II. For the chaotic states, however, the reported SBS values should be interpreted with caution, as the absence of persistent coherent structures renders the notion of a well-defined SBS less meaningful.

The overall phase behavior in Fig. 4 exhibits an interesting correspondence with the $\omega/D_r - \Omega_a/\Omega_v$ state diagram. Rotary clusters appear upon increasing the chirality in the latter, whereas in the former they are recovered within specific ranges of the vision angle. This suggests that increasing the intrinsic chirality and tuning the vision angle can play qualitatively similar roles in promoting the emergence of rotary clusters. A detailed investigation of this correspondence, however, lies beyond the scope of the present work.

Table II provides short definitions of the distinct states observed.

C. Dynamical properties

1. Mean-square displacement

To investigate the system's dynamical properties, we begin by characterizing its translational dynamics. This is quantified using the mean-square displacement (MSD) of all particles, defined as

$$\langle r^2(t) \rangle = \frac{1}{N} \sum_{i=1}^N \langle (r_i(t + t_0) - r_i(t_0))^2 \rangle_{t_0}. \quad (6)$$

We compare the MSD of the emergent states with that of a single chiral ABP [54,55]. Figure 5 shows the resulting MSD curves together with that of a single chiral ABP.

A key observation is that the MSD of emergent collective states exceeds that of a single chiral ABP, which is consistent with expectations due to collective effects. Ripple and

wormlike states display ballistic behavior, characterized by $\langle r^2(t) \rangle \sim t^2$, over short to intermediate timescales, eventually transitioning to a subdiffusive regime at longer times. In contrast, vortex and rotating cluster states also exhibit ballistic scaling at intermediate times but transition to oscillatory behavior at long times. Rotary clusters display stronger chirality than single particles under the same conditions. These oscillations stem from the coherent collective rotation of particles in these states. Interestingly, spinner states do not exhibit such oscillations—at least up to intermediate times—likely due to their very long rotational timescales, resulting from the absence of the local orientational order found in vortex and rotating cluster states.

The scaling exponents are estimated from the approximately linear regions of the log-log MSD curves. The straight-line fits are intended only to highlight the dominant dynamical behavior over these intervals, with no pronounced curvature or crossover observed within the displayed time range.

2. Mean-square angular displacement

Analogous to the translational dynamics quantified by the MSD, the rotational dynamics of the particles can be charac-

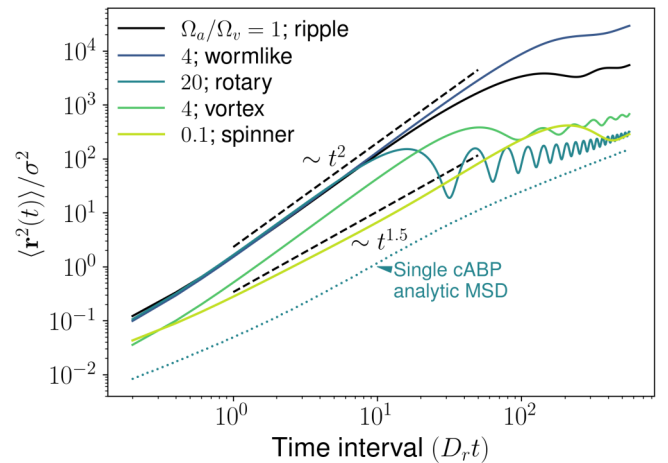


FIG. 5. Mean-square displacements of the dominant collective states: Only the distinct, stable configurations are shown. Worms remain ballistic across most timescales, while spinners are superdiffusive at short-intermediate times but exhibit oscillatory behavior at longer times. The dotted line marked “single cABP analytic MSD” shows the MSD of a single chiral ABP. Rotary clusters exhibit stronger chirality than single particles under the same conditions. Data are averaged over ten runs. Parameters: $\theta = \pi/4$ for all states (Fig. 4), except for the vortex state at $\theta = \pi/2$.

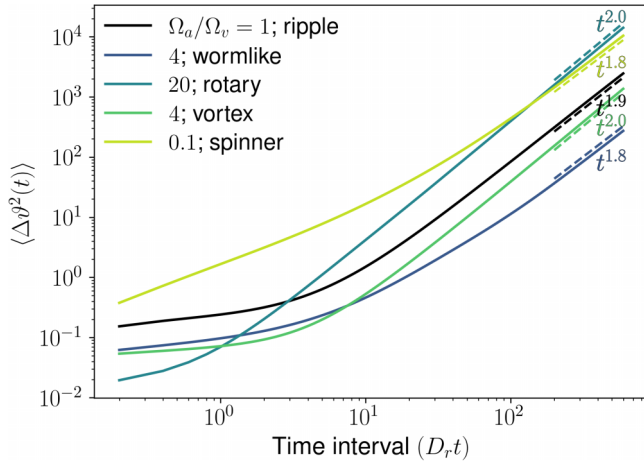


FIG. 6. Mean-square angular displacements of the dominant collective states: We include only the most stable and well-defined configurations. All data are averaged over ten independent simulation runs. Parameters: $\theta = \pi/4$ for all states (Fig. 4), except for the vortex state at $\theta = \pi/2$.

terized by the mean-squared angular displacement (MSAD), defined as

$$\langle \Delta \vartheta^2(t) \rangle = \frac{1}{N} \sum_{i=1}^N \langle (\vartheta_i(t + t_0) - \vartheta_i(t_0))^2 \rangle_{t_0}. \quad (7)$$

The corresponding results are presented in Fig. 6. Particles, collectively, in the rotary and vortex structures shows proper ballistic angular displacement ($\langle \Delta \vartheta^2(t) \rangle \sim t^2$), whereas in spinner, ripple, and worm it is reduced.

3. Orientation correlation function

Another key quantity that characterizes the collective dynamics of the swarm is the orientation correlation function (OCF), also known as the temporal autocorrelation function. It is defined as

$$C_\theta(t) = \frac{1}{N} \sum_{i=1}^N \langle \mathbf{e}_i(t + t_0) \cdot \mathbf{e}_i(t_0) \rangle_{t_0}. \quad (8)$$

The corresponding plots are presented in Figs. 7 and 8. Figure 7 shows the OCFs for spinners, ripples, and worms, with worms decaying much more slowly than ripples and spinners exhibiting the fastest decay. These timescales reflect the decreasing order of alignment strength, $\Omega_a/\Omega_v = 4, 1$, and 0.1 , for the chosen states. In essence, stronger alignment leads to a longer OCF decay timescale.

In Fig. 8, we present the OCF for rotary cluster and vortex state. As noted in Secs. IV A and IV B, rotary clusters typically emerge for $\Omega_a > \Omega_v$, reflecting enhanced chirality. This is also evident from the trajectories shown in the Video M6 of the Supplemental Material [40]. However, when averaged over all particles and multiple realizations, the chirality of the rotary cluster shows a slight deviation from the single-particle estimate. The OCF for the rotary cluster, fitted with

$$y = A \cos(\omega t + B) e^{-t/\tau_d}, \quad (9)$$

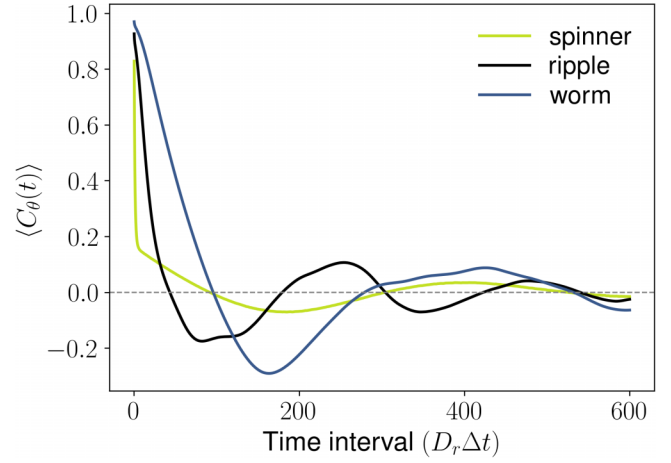


FIG. 7. Orientation correlation functions of representative collective states: The most stable configurations are selected for analysis. Shown here are the OCFs of spinner, ripple, and wormlike clusters. Data are averaged over ten independent realizations. The parameters are $\theta = \pi/4$ with $\Omega_a/\Omega_v = 0.1, 1$, and 4 for spinner, ripple and worm, respectively.

is shown in the upper panel of Fig. 8. Expressed in terms of the dimensionless chirality, the fitted value is $\omega/D_r = 0.1975$, which is lower than the imposed value of 0.25 . The correlation decay time is $\tau_d \sim 536.23 D_r t$. A similar reduction in the collective rotational speed has been reported in Ref. [22], where rotating macrodroplets surrounded by a dilute gas of particles were found to rotate more slowly than the constituent chiral ABPs. The authors further showed analytically that this slowdown is a consequence of the density-alignment coupling, leading to an interaction-induced renormalization of the effective chirality.

The same fitting as Eq. (9), applied to the OCF of the vortex, yields $\omega/D_r = 0.0702$ and a correlation decay time $\tau_d \sim 1009 D_r t$. This decay timescale τ_d may be associated with structural relaxation within the cluster and is expected to be longer for close-packed vortices and shorter for rotary clus-

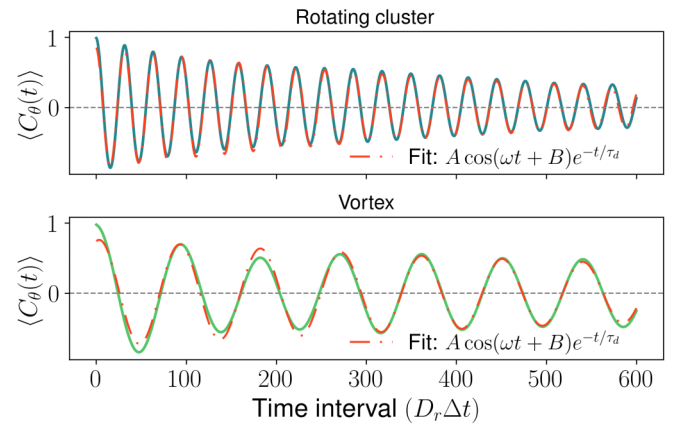


FIG. 8. Orientation correlation functions of rotary and vortex clusters. For both of the states, the OCF is fitted to extract the characteristic oscillation frequency. Data are averaged over ten independent realizations. The parameters are $\theta = \pi/4$ with $\Omega_a/\Omega_v = 20$ for rotary and $\theta = \pi/2$ with $\Omega_a/\Omega_v = 4$ for the vortex.

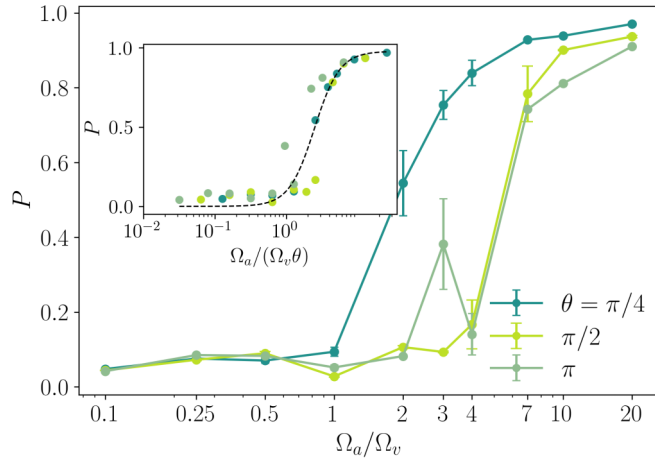


FIG. 9. Global polarization as a function of the maneuverability ratio Ω_a/Ω_v for three different vision angles: π , $\pi/2$, and $\pi/4$. The data are shown for $Pe = 10$ and $\omega/D_r = 0.25$. Error bars denote the standard error of the mean; long error bars indicate coexistence of multiple states within that parameter regime. The description of the inset is given in the text.

ters. The fitted angular frequency (ω/D_r) reflects the spinning period of a vortex, which is further supported by Fig. 4, where the solid-body spin of vortices attains significantly higher values (~ 0.07). It also indicates that for a rotary cluster the fitted ω/D_r is not associated with spinning rather with the orbital period.

Global alignment decreases steadily from the rotary cluster to the vortex and ultimately to the spinner state. In the spinner state, orientational order is entirely absent (also discussed later), whereas in the vortex state strongly aligned patches persist. The presence of these patches leads to positional shifts of the entire vortex cluster, though in an incoherent way (see Movie M7 in the Supplemental Material [40]).

D. Structural properties

1. Global polarization

The global polarization is defined as

$$P = \left\langle \frac{1}{N} \left| \sum_i \mathbf{e}_i \right| \right\rangle, \quad (10)$$

where $\mathbf{e}_i$ denotes the unit orientation vector of particle i and $\langle \cdot \rangle_t$ is a time average. This quantity measures the degree of polar order in the system, i.e., how well the particles align with each other. A large value of P corresponds to strong alignment, commonly referred to as flocking. The results are presented in Fig. 9.

Global polarization serves as an order parameter that distinguishes between different emergent states. Figure 9 shows P versus the maneuverability ratio Ω_a/Ω_v for several vision angles. For small Ω_a/Ω_v , polarization remains close to zero regardless of vision angle, reflecting weak aligning interactions. As Ω_a/Ω_v increases, polarization develops, but the onset depends strongly on the vision angle: Larger vision angles require higher alignment strength to induce nonzero

polarization. This dataset corresponds to $Pe = 10$ and $\omega/D_r = 0.25$.

Up to $\Omega_a/\Omega_v = 1$, ripples, vortices, and spinning clusters are obtained for the vision angles considered here. None of them show any significant net directional alignment, resulting in almost vanishing P values. For moderate Ω_a/Ω_v values, net polarization starts depending on the vision angles, with lower θ forming more aligned structures. At around $\theta = \pi/4$, wormlike swarms start forming from $\Omega_a/\Omega_v \sim 2$; consequently, P starts growing. But the dominant configurations at $\theta = \pi/2$ and π are vortices; some realizations of $\Omega_a/\Omega_v \sim 3$ at $\theta = \pi$ show vortices, while others show close-to-rotary structures—indicating possible multistability, thus showing the peak.

For large values of Ω_a/Ω_v , $\theta = \pi/2$ gives well-formed and stable wormlike swarms, whereas $\theta = \pi/4$ and π gives rotary clusters. Rightmost part of Fig. 9 shows that the rotary structures—even though qualitatively showing a reentrance for high and low vision angles—differ in internal ordering for different vision angles.

As shown in Fig. 9, the growth of the net polarization with Ω_a/Ω_v depends systematically on the vision angle. For smaller θ , polar order develops at lower values of Ω_a/Ω_v , indicating that reducing the angular range of visual perception has an effect similar to increasing the relative importance of alignment. This suggests that the competition between polar alignment and vision-mediated steering is not fully captured by the bare ratio Ω_a/Ω_v alone.

A simple way to account for this dependence is to recognize that the number and angular distribution of neighbors contributing to the visual torque change with the vision cone. In a homogeneous configuration, the number of particles inside the cone scales approximately with its angular width, $N_{\text{vis}} \sim \theta$. This suggests an effective visual contribution of $\Omega_v \theta$. We therefore examine the polarization as a function of the scaled ratio $\Omega_a/(\Omega_v \theta)$. As shown in the inset of Fig. 9, this rescaling produces an approximate collapse of the polarization data for different vision angles. Within the explored parameter range, the collapse indicates that $\Omega_a/(\Omega_v \theta)$ provides a useful measure of the competition between alignment and vision-mediated steering. The rapid increase of P around $\Omega_a/(\Omega_v \theta) \sim 2$ marks the crossover from weakly polarized, rotation-dominated states to strongly polarized, alignment-dominated collective motion.

2. Solid-body spin

To explicitly characterize rotational motion using actual particle dynamics, we compute velocities from particle displacements and define the solid-body spin of a cluster as

$$\Omega_{\text{cl}} = \frac{\sum_i (\mathbf{r}_i^c \times \mathbf{v}_i^c)_z}{\sum_i |\mathbf{r}_i^c|^2}. \quad (11)$$

Here, $\mathbf{r}_i^c = \mathbf{r}_i - \mathbf{r}_{\text{cm}}$ denotes the position of the i th particle relative to the cluster center of mass, and $\mathbf{v}_i^c = \mathbf{v}_i - \mathbf{v}_{\text{cm}}$ is its velocity relative to the center-of-mass velocity.

Velocities entering Eq. (11) are obtained using a central-difference scheme, $\mathbf{v}(t) = [\mathbf{x}(t + \Delta t) - \mathbf{x}(t - \Delta t)]/(2\Delta t)$. The resulting (nondimensionalized) time-averaged absolute SBS ($\langle |\Omega_{\text{cl}}| \rangle / D_r$) heatmap is shown in Fig. 4. Rotary

states exhibit the weakest solid-body rotation ($(|\Omega_{cl}|)/D_r \lesssim 0.015$). Spinners show moderately larger but still low values (≈ 0.015), substantially smaller, due to their low angular speeds. In contrast, vortices attain the largest SBS values, reflecting both their coherent internal structure and high rotation rates; a similar behavior is observed for ripples. The computed SBS value of the vortices (Fig. 4) is consistent with the value of $\omega/D_r = 0.0702$ as obtained from the OCF. Wormlike states also display weak solid-body rotation—perhaps a feature of its instantaneous shape, while chaotic aggregates—often composed of fragmented or dispersed clusters—exhibit negligible SBS.

E. Structural analysis of ripple state

Before analyzing the structural properties of ripple clusters, it is useful to distinguish them from superficially similar states such as vortices. As discussed in Sec. IV A, ripple formation (expanding loops) arises from the interplay of strong visual maneuverability and a sufficiently large cluster, which generates a net outward torque on particles near the vortex core, breaking local symmetry and driving loop expansion. This naturally raises the question of whether the ripple represents a genuine collective state or merely a finite-size artifact arising from the interplay between system size and visual torque strength. Our finite-size analysis, presented in the Supplemental Material [40], shows that ripple formation first appears above a threshold system size and persists for all larger systems investigated over an increasingly broad range of maneuverability ratios. Since increasing Ω_a/Ω_v strengthens the alignment interaction relative to the visual interaction, ripple formation is expected to become progressively more difficult. However, we find the opposite trend with system size: As the system becomes larger, ripples remain stable over a broader range of Ω_a/Ω_v . This indicates that larger clusters enhance the robustness of the visual-torque-driven expansion, allowing it to withstand stronger competing alignment interactions. This interpretation is also consistent with the observation in Sec. IV B that sufficiently strong alignment ultimately suppresses ripple expansion and produces compact vortices. Taken together, these results support the conclusion that ripples are a genuine collective state that emerges only when a sufficiently large cluster and strong visual maneuverability act together in the presence of steric interactions.

1. Quantitative descriptors

To characterize ripple clusters, we employ several quantities:

Asphericity. The shape asymmetry is quantified via

$$A = \frac{|I_1 - I_2|}{I_1 + I_2}, \quad (12)$$

where I_1 and I_2 are the principal moments of inertia. Here, $A = 0$ corresponds to a perfectly circular loop, while $A = 1$ means large deviation from circularity.

Cluster circulation index and angular frequency. The cluster circulation index—a diagnostic that quantifies the degree of coherent tangential motion around the cluster center, and the cluster-averaged angular frequency are defined,

respectively, as [35,53,56]

$$\mathcal{C}(t) = \frac{1}{N_c} \sum_{i=1}^{N_c} \left(\frac{\mathbf{r}_i^c(t) - \mathbf{r}_{cm}^c(t)}{|\mathbf{r}_i^c(t) - \mathbf{r}_{cm}^c(t)|} \times \hat{\mathbf{e}}_i(t) \right) \quad (13)$$

and

$$\nu(t) = \frac{1}{N_c} \frac{|\sum_i (\mathbf{r}_i^c(t) - \mathbf{r}_{cm}^c(t)) \times \hat{\mathbf{e}}_i(t)|}{\sum_i (\mathbf{r}_i^c(t) - \mathbf{r}_{cm}^c(t))^2}, \quad (14)$$

where N_c is the number of particles in the cluster, $\mathbf{r}_i^c(t)$ the position of the i th particle, $\mathbf{r}_{cm}^c(t)$ the cluster center of mass, and $\hat{\mathbf{e}}_i(t)$ the particle orientation. Note that, by construction, $\mathcal{C}(t)$ is dimensionless, whereas $\nu(t)$ has the dimension of inverse length. Further, SBS is equivalent to angular frequency and in Eq. (11), SBS is defined using particle velocities, obtained from the particle displacements, rather than orientation vectors, because the particle motion does not necessarily align with the particle orientations in certain states, such as the rotating cluster and the vortex states (data not shown). A comparison between the temporal evolution of the angular frequency and the SBS for the ripple state is provided in the Supplemental Material [40].

Cluster radius. The average cluster radius is defined as

$$R(t) = \frac{1}{N_c} \sum_{i=1}^{N_c} \sqrt{(\mathbf{r}_i(t) - \mathbf{r}_{cm}(t))^2}. \quad (15)$$

2. Ripple dynamics

The behavior of these descriptors is summarized in Fig. 10. Each quantity is shown for both ripples that undergo breakup-reformation cycles and for those that remain intact. The plots indicate that ripple breakup occurred at $\sim 1400D_r t$. After breakup, the average ripple radius $R_{av}(t)/\sigma$ increases slowly, reflecting the longer time required for reformation after restarting from the dense configuration. In contrast, other descriptors such as the cluster circulation index $\mathcal{C}(t)$ and the asphericity $A(t)$ recover almost immediately. The cluster-averaged angular frequency $\nu(t)\sigma$ rises sharply after breakup and then gradually decreases in tandem with $R_{av}(t)/\sigma$. Overall, ripple loops expand steadily while their rotation rate slows down. The near constancy of $\mathcal{C}(t)$ across breakup event indicates that the tangential orientational order underlying the loop structure is largely maintained even across breakup events. Finally, the low asphericity shows the loop remains close to circular except under strong perturbations.

3. Internal structure

As discussed in Sec. IV A and illustrated in Fig. 2 (3), ripple loops possess a characteristic internal organization: Inner particles tilt outward, outer particles tilt inward, and intermediate particles align tangentially. To verify this, we compute the probability distribution of the radial orientation component $\mathcal{P}(e_r)$, defined as [57]

$$e_{ri} = \hat{\mathbf{e}}_i \cdot \hat{\mathbf{r}}_i = \cos(\Delta_i),$$

where $\hat{\mathbf{e}}_i$ is the orientation of particle i , $\hat{\mathbf{r}}_i$ is the radial unit vector from the cluster center of mass, and Δ_i is the angle between them. Thus, $e_{ri} > 0$ corresponds to outward-pointing

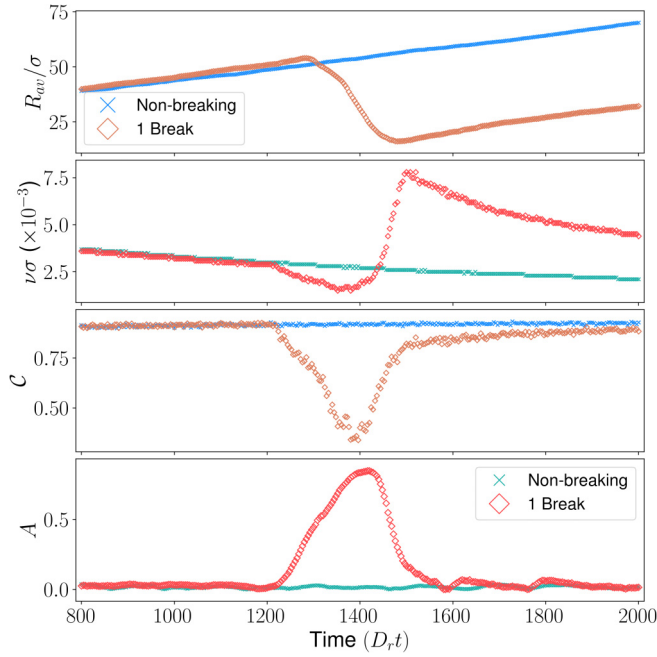


FIG. 10. From top to bottom: (a) Average ripple radius $R_{av}(t)/\sigma$. The blue curve shows steady growth, while the red curve corresponds to a loop that temporarily broke, reformed, and continued to expand. No fragmentation occurred. (b) Angular frequency $\nu\sigma$ decreases as the ripple expands, indicating slower rotation for larger loops. (c) Cluster circulation index C remains nearly constant except during breakup events. (d) Asphericity A indicates that ripples remain close to circular in shape unless disrupted. No ensemble averaging was performed, since ripple dynamics (growth, breakup, reformation, fragmentation) are highly unpredictable, and averaging would obscure these distinctive behaviors.

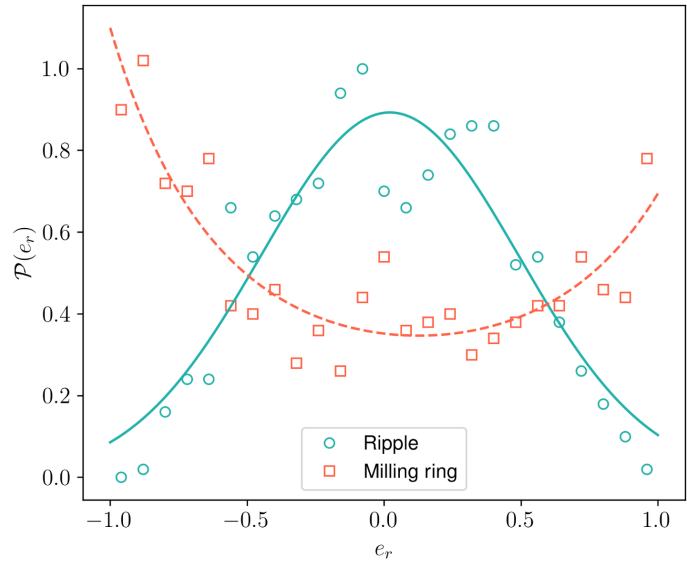
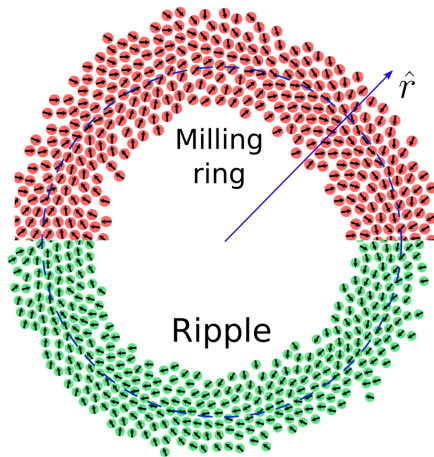


FIG. 11. Left: The figure illustrates the difference in orientational configurations of particles in a milling ring (top) and a ripple (bottom). The ripple shown here is at an early stage of expansion, with a radius comparable to that of the milling ring. In the milling ring, radially inward- and outward-oriented particles dominate over tangentially oriented ones. Both states are observed within the same parameter regime as in the right figure. Right: Probability distribution $\mathcal{P}(e_r)$ of the radial orientation component for a ripple and a milling ring both in their well-formed region. Ripple: $\Omega_a/\Omega_v = 1$ and $\theta = \pi/3$, milling ring: $\Omega_a/\Omega_v = 1$ and $\theta = \pi/2$. Fitting: $\exp\{-(x - \mu)^2/\sigma^2\}$ and $\exp\{(x - \mu)^2/\sigma^2\}$, respectively.

orientations, $e_{ri} < 0$ to inward-pointing ones, and $e_{ri} = 0$ to tangential orientations. The results are shown in Fig. 11.

Figure 11 compares the radial orientation component of ripple and milling states. The ripple exhibits predominantly tangential orientations with nearly balanced radial components. The milling ring shows strong inward bias and reduced tangential alignment. This generates an effective inward pressure that hinders expansion.

4. Mechanistic study: Torque behavior across different states

A key question concerns the origin of ripple expansion. Here, we examine this by analyzing the roles of visual and alignment torques. As noted in Sec. IV A, ripples and milling rings are morphologically similar to vortices, with ripple formation associated with dominant visual torque. Since the emergent states are governed by the competition between visual and alignment interactions (with chirality acting at the single-particle level), we analyze the time evolution of the mean absolute visual and alignment torques, averaged over all particles (Fig. 12).

We find that alignment torque dominates across all vortex-like states. However, while the milling ring remains similar to a compact vortex, the ripple shows a distinct temporal evolution of $\langle |\tau_v| \rangle$. As the ripple expands, the effective visual torque increases gradually, followed by a sharp drop during breakup, and a subsequent recovery upon reformation. This corroborates with our claim that stronger visual torque is a prerequisite for ripple expansion.

V. CONCLUSIONS

In this work, we extend perception-driven models of intelligent active Brownian particles with polar alignment by

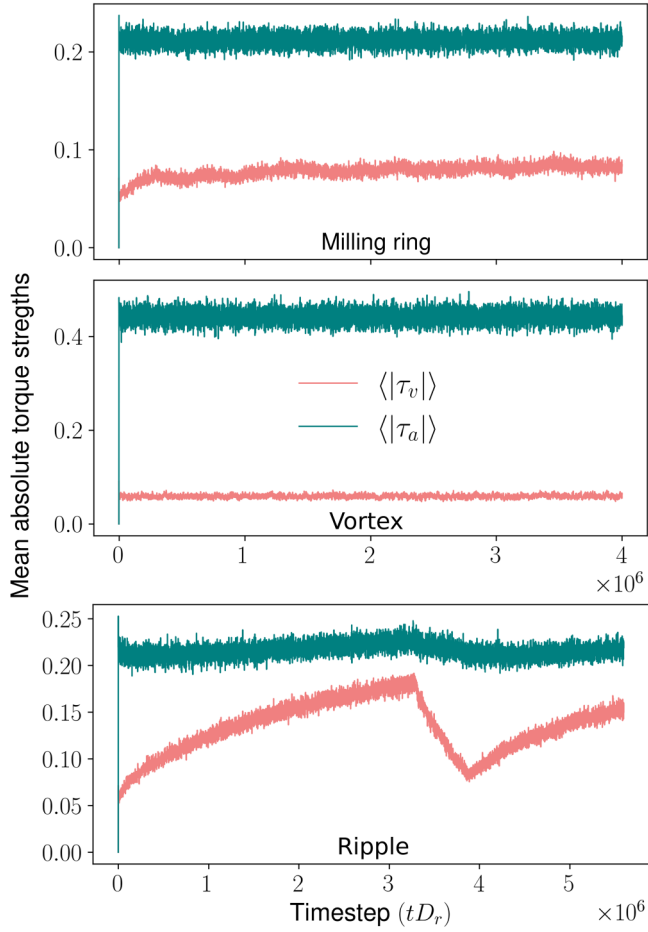


FIG. 12. Variation of the mean absolute visual and alignment torques, $\langle |\tau_v| \rangle$ and $\langle |\tau_a| \rangle$, averaged over all particles. Top to bottom: Milling ring (parameters: $\Omega_a/\Omega_v = 1$, $\theta = \pi/2$), vortex ($\Omega_a/\Omega_v = 4$, $\theta = \pi/2$), and ripple ($\Omega_a/\Omega_v = 1$, $\theta = \pi/3$). The ripple spans a longer time interval, capturing its formation, breakup, and subsequent reformation.

incorporating intrinsic chirality. By systematically varying the chirality, vision angle, and the competition between alignment and visual maneuverability, we construct two dynamical state diagrams revealing a rich variety of emergent states, including spinners, vortices, ripples, wormlike swarms, and rotary clusters.

Previous studies of visually interacting active systems have shown that additional ingredients, such as delayed interactions, misaligned perception, and stochastic acceleration, can give rise to collective states commonly associated with chiral dynamics, including vortices, spinners, and milling rings [32,35,43,48–52]. Motivated by the ubiquity of chiral motion in active matter and the fact that intrinsic rotation is a fundamental single-particle property, we investigated its role in visually interacting systems. Our results demonstrate that intrinsic chirality alone can generate collective behavior qualitatively similar to that previously attributed to delayed or misaligned-perception effects. Moreover, in combination with nonreciprocal vision-based interactions, chirality gives rise to additional dynamical states, including ripples and rotary clusters, which are absent in the corresponding systems with purely linear self-propulsion.

Our findings position perception-driven active systems within the broader family of alignment-based models and show that the interplay between intrinsic chirality and anisotropic visual interactions qualitatively transforms collective behavior. Chirality acts as a competing timescale that governs whether the system forms compact rotating aggregates, vortices, wormlike swarms, or extended cohesive structures. Ripple loops, in particular, emerge as a distinct vision-dominated dynamical regime driven by outward torques acting on central particles and are stabilized only when the particle number is sufficiently large and visual maneuverability dominates.

The observed states can be systematically distinguished using a small set of structural and dynamical measures, summarized in Table III. Solid-body spin separates strongly rotating vortices from weakly spinning spinners and rotary clusters, polarization captures the transition from weak to strong internal ordering, and orientation correlations quantify the persistence of local orientational order. Together, these measures provide a unified framework for classifying the collective states across the explored parameter space.

Therefore, our results demonstrate that intrinsic chirality does more than perturb the vision-cone model of Negi *et al.* [35]. Rather, by continuously rotating the direction of motion relative to the sensing sector, chirality fundamentally reshapes the effective interaction network, giving rise to collective states and transitions that cannot be inferred from chiral active matter with isotropic interactions or nonchiral vision-cone models in isolation. Overall, our work bridges

TABLE III. Distinct states and qualitative comparison across parameter regimes.

State	MSD	MSAD (long time)	Orientation correlation	Polarization	Angular frequency/ solid-body spin
Worms	Intermediate: ballistic	Superdiffusive	Very fast decay	Very high	Low
Spinners	Intermediate: superdiffusive long: oscillatory	Superdiffusive	Fastest decay	~ 0	Low
Vortices	Intermediate: ballistic long: oscillatory	Ballistic	Oscillatory (spinning)	Very low	High
Ripples	Intermediate: superdiffusive long: oscillatory	Superdiffusive	Very fast decay	~ 0	High
Rotary states	Short: ballistic intermediate-long: oscillatory	Ballistic	Oscillatory (orbiting)	Very high	Very low

two active-matter settings that are often treated separately—chiral aligning systems and perception-based, nonreciprocal models—and shows that their interplay gives rise to emergent collective dynamics beyond those produced by either framework individually. Future work could examine how these phenomena depend on density, confinement, and dimensionality, and whether related ripplelike or vortexlike structures persist in three-dimensional systems or experimentally realizable chiral active suspensions.

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Authors declare no competing interests.

DATA AVAILABILITY

The data associated with the figures are available [59].

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- [1] M. C. Marchetti, J.-F. Joanny, S. Ramaswamy, T. B. Liverpool, J. Prost, M. Rao, and R. A. Simha, Hydrodynamics of soft active matter, *Rev. Mod. Phys.* **85**, 1143 (2013).
 - [2] E. Bonabeau, G. Theraulaz, J.-L. Deneubourg, S. Aron, and S. Camazine, Self-organization in social insects, *Trends Ecol. Evol.* **12**, 188 (1997).
 - [3] S. Camazine, J.-L. Deneubourg, N. R. Franks, J. Sneyd, G. Theraulaz, and E. Bonabeau, *Self-Organization in Biological Systems* (Princeton University Press, Princeton, NJ, 2003).
 - [4] T. Vicsek and A. Zafeiris, Collective motion, *Phys. Rep.* **517**, 71 (2012).
 - [5] C. Bechinger, R. Di Leonardo, H. Löwen, C. Reichhardt, G. Volpe, and G. Volpe, Active particles in complex and crowded environments, *Rev. Mod. Phys.* **88**, 045006 (2016).
 - [6] P. Romanczuk, M. Bär, W. Ebeling, B. Lindner, and L. Schimansky-Geier, Active Brownian particles: From individual to collective stochastic dynamics, *Eur. Phys. J.: Spec. Top.* **202**, 1 (2012).
 - [7] J. Elgeti, R. G. Winkler, and G. Gompper, Physics of microswimmers—Single particle motion and collective behavior: A review, *Rep. Prog. Phys.* **78**, 056601 (2015).
 - [8] P. Patra, K. Beyer, A. Jaiswal, A. Battista, K. Rohr, F. Frischknecht, and U. S. Schwarz, Collective migration reveals mechanical flexibility of malaria parasites, *Nat. Phys.* **18**, 586 (2022).
 - [9] L. Lettermann, M. Singer, S. Steinbrück, F. Ziebert, S. Kanatani, P. Sinnis, F. Frischknecht, and U. S. Schwarz, Chirality of malaria parasites determines their motion patterns, *Nat. Phys.* **22**, 112 (2026).
 - [10] H. C. Berg and L. Turner, Chemotaxis of bacteria in glass capillary arrays. *Escherichia coli*, motility, microchannel plate, and light scattering, *Biophys. J.* **58**, 919 (1990).
 - [11] I. H. Riedel, K. Kruse, and J. Howard, A self-organized vortex array of hydrodynamically entrained sperm cells, *Science* **309**, 300 (2005).
 - [12] W. R. DiLuzio, L. Turner, M. Mayer, P. Garstecki, D. B. Weibel, H. C. Berg, G. M. Whitesides, *Escherichia coli* swim on the right-hand side, *Nature (London)* **435**, 1271 (2005).
 - [13] E. Lauga, W. R. DiLuzio, G. M. Whitesides, and H. A. Stone, Swimming in circles: Motion of bacteria near solid boundaries, *Biophys. J.* **90**, 400 (2006).
 - [14] B. M. Friedrich and F. Jülicher, Chemotaxis of sperm cells, *Proc. Natl. Acad. Sci. USA* **104**, 13256 (2007).
 - [15] E. Lauga and T. R. Powers, The hydrodynamics of swimming microorganisms, *Rep. Prog. Phys.* **72**, 096601 (2009).
 - [16] B. M. Friedrich and F. Jülicher, Steering chiral swimmers along noisy helical paths, *Phys. Rev. Lett.* **103**, 068102 (2009).
 - [17] D. Takagi, J. Palacci, A. B. Braunschweig, M. J. Shelley, and J. Zhang, Hydrodynamic capture of microswimmers into sphere-bound orbits, *Soft Matter* **10**, 1784 (2014).
 - [18] X. Wang, P.-C. Chen, K. Kroy, V. Holubec, and F. Cichos, Spontaneous vortex formation by microswimmers with retarded attractions, *Nat. Commun.* **14**, 56 (2023).
 - [19] F. Kümmel, B. T. Hagen, R. Wittkowski, I. Buttinoni, R. Eichhorn, G. Volpe, H. Löwen, and C. Bechinger, Circular motion of asymmetric self-propelling particles, *Phys. Rev. Lett.* **110**, 198302 (2013).
 - [20] V. Kaur, S. S. Khuntia, C. Taneja, A. Chaudhuri, K. P. Yogendran, and S. Rakshit, *De-novo* design of actively spinning and gyrating spherical micro-vesicles, *Adv. Mater.* **37**, 2419716 (2025).
 - [21] T. Vicsek, A. Czirók, E. Ben-Jacob, I. Cohen, and O. Shochet, Novel type of phase transition in a system of self-driven particles, *Phys. Rev. Lett.* **75**, 1226 (1995).
 - [22] B. Liebchen and D. Levis, Collective behavior of chiral active matter: Pattern formation and enhanced flocking, *Phys. Rev. Lett.* **119**, 058002 (2017).
 - [23] D. Levis, I. Pagonabarraga, and B. Liebchen, Activity induced synchronization: Mutual flocking and chiral self-sorting, *Phys. Rev. Res.* **1**, 023026 (2019).
 - [24] B. Ventéjou, H. Chaté, Raul Montagne, and Xia-qing Shi, Susceptibility of orientationally ordered active matter to chirality disorder, *Phys. Rev. Lett.* **127**, 238001 (2021).
 - [25] Y. Wang, B. Ventéjou, Hugues Chaté, and Xia-qing Shi, Condensation and synchronization in aligning chiral active matter, *Phys. Rev. Lett.* **133**, 258302 (2024).

- [26] D. Levis and B. Liebchen, Simultaneous phase separation and pattern formation in chiral active mixtures, *Phys. Rev. E* **100**, 012406 (2019).
- [27] D. Levis and B. Liebchen, Micro-flock patterns and macro-clusters in chiral active Brownian disks, *J. Phys.: Condens. Matter* **30**, 084001 (2018).
- [28] L. Caprini, B. Liebchen, and H. Löwen, Self-reverting vortices in chiral active matter, *Commun. Phys.* **7**, 153 (2024).
- [29] L. Barberis and F. Peruani, Large-scale patterns in a minimal cognitive flocking model: Incidental leaders, nematic patterns, and aggregates, *Phys. Rev. Lett.* **117**, 248001 (2016).
- [30] R. Bastien and P. Romanczuk, A model of collective behavior based purely on vision, *Sci. Adv.* **6**, eaay0792 (2020).
- [31] F. A. Lavergne, H. Wendehehne, T. Bäuerle, and C. Bechinger, Group formation and cohesion of active particles with visual perception-dependent motility, *Science* **364**, 70 (2019).
- [32] R. Saavedra, G. Gompper, and M. Ripoll, Swirling due to misaligned perception-dependent motility, *Phys. Rev. Lett.* **132**, 268301 (2024).
- [33] R. Saavedra and M. Ripoll, Directed swarm assembly due to mixed misaligned perception-dependent motility, *Commun. Phys.* **8**, 203 (2025).
- [34] R.-x. Guo, J.-j. Li, F.-g. Li, and B.-q. Ai, Rectification and collective dynamics of active particles driven by misaligned perception-dependent motility, *Phys. Rev. E* **111**, 055410 (2025).
- [35] R. S. Negi, R. G. Winkler, and G. Gompper, Collective behavior of self-steering active particles with velocity alignment and visual perception, *Phys. Rev. Res.* **6**, 013118 (2024).
- [36] Z. Liu and M. Dijkstra, Collective dynamics of intelligent active Brownian particles with visual perception and velocity alignment in 3D: Spheres, rods, and worms, *Soft Matter* **21**, 1529 (2025).
- [37] K. L. Kreienkamp and S. H. L. Klapp, Nonreciprocal alignment induces asymmetric clustering in active mixtures, *Phys. Rev. Lett.* **133**, 258303 (2024).
- [38] R. S. Negi, R. G. Winkler, and G. Gompper, Binary mixtures of intelligent active Brownian particles with visual perception, *New J. Phys.* **27**, 103301 (2025).
- [39] R. S. Negi, R. G. Winkler, and G. Gompper, Emergent collective behavior of active Brownian particles with visual perception, *Soft Matter* **18**, 6167 (2022).
- [40] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/x14x-yykw> for description of supplementary movies, discussion on higher Pé number, finite-size analysis of the ripple, and comparison of SBS and angular frequency, which includes Refs. [35,53,58].
- [41] A. P. Thompson, H. M. Aktulga, R. Berger, D. S. Bolintineanu, W. M. Brown, P. S. Crozier, A. Kohlmeyer, S. G. Moore, T. D. Nguyen, *et al.*, LAMMPS—A flexible simulation tool for particle-based materials modeling at the atomic, meso, and continuum scales, *Comput. Phys. Commun.* **271**, 108171 (2022).
- [42] J. T. Siebert, F. Dittrich, F. Schmid, K. Binder, T. Speck, and P. Virnau, Critical behavior of active Brownian particles, *Phys. Rev. E* **98**, 030601(R) (2018).
- [43] M. Durve, A. Saha, and A. Sayeed, Active particle condensation by non-reciprocal and time-delayed interactions, *Eur. Phys. J. E* **41**, 49 (2018).
- [44] G.-J. Liao and S. H. L. Klapp, Clustering and phase separation of circle swimmers dispersed in a monolayer, *Soft Matter* **14**, 7873 (2018).
- [45] H. Wioland, F. G. Woodhouse, J. Dunkel, J. O. Kessler, and R. E. Goldstein, Confinement stabilizes a bacterial suspension into a spiral vortex, *Phys. Rev. Lett.* **110**, 268102 (2013).
- [46] A. Bricard, J.-B. Caussin, D. Das, C. Savoie, V. Chikkadi, K. Shitara, O. Chepizhko, F. Peruani, D. Saintillan, and D. Bartolo, Emergent vortices in populations of colloidal rollers, *Nat. Commun.* **6**, 7470 (2015).
- [47] Z.-F. Huang, A. M. Menzel, and H. Löwen, Dynamical crystallites of active chiral particles, *Phys. Rev. Lett.* **125**, 218002 (2020).
- [48] J. P. Newman and H. Sayama, Effect of sensory blind zones on milling behavior in a dynamic self-propelled particle model, *Phys. Rev. E* **78**, 011913 (2008).
- [49] A. Costanzo and C. K. Hemelrijk, Spontaneous emergence of milling (vortex state) in a Vicsek-like model, *J. Phys. D: Appl. Phys.* **51**, 134004 (2018).
- [50] A. Costanzo, E. van Haeringen, and C. K. Hemelrijk, Effect of time-delayed interactions on milling: A minimal model, *Europhys. Lett.* **138**, 22002 (2022).
- [51] D. S. Calovi, U. Lopez, S. Ngo, C. Sire, Hugues Chaté, and Guy Theraulaz, Swarming, schooling, milling: Phase diagram of a data-driven fish school model, *New J. Phys.* **16**, 015026 (2014).
- [52] T. Bagarti and S. N. Menon, Milling and meandering: Flocking dynamics of stochastically interacting agents with a field of view, *Phys. Rev. E* **100**, 012609 (2019).
- [53] J. Shea and H. Stark, Emergent collective behavior of cohesive, aligning particles, *Eur. Phys. J. E* **48**, 22 (2025).
- [54] S. van Teeffelen and H. Löwen, Dynamics of a Brownian circle swimmer, *Phys. Rev. E* **78**, 020101(R) (2008).
- [55] A. Pattanayak, A. Shee, D. Chaudhuri, and A. Chaudhuri, Impact of torque on active Brownian particle: Exact moments in two and three dimensions, *New J. Phys.* **26**, 083024 (2024).
- [56] I. D. Couzin, J. Krause, R. James, G. D. Ruxton, and N. R. Franks, Collective memory and spatial sorting in animal groups, *J. Theor. Biol.* **218**, 1 (2002).
- [57] R. Saavedra and F. Peruani, Self-trapping of active particles with nonreciprocal interactions in disordered media, *Phys. Rev. E* **110**, 064602 (2024).
- [58] F. J. Sevilla and P. Castro-Villarreal, Generalized persistence dynamics for active motion, *Phys. Rev. E* **104**, 064601 (2021).
- [59] <https://github.com/bhaskardiganta/cABP-vision-align>.