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Noise-Induced Resonance in Periodically Driven Run-and-Tumble Bacterial Suspensions

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ABSTRACT

Noise is generally regarded as a source of disorder in active matter, yet its role in periodically driven bacterial suspensions remains poorly understood. Here, we use particle-based simulations to investigate whether stochastic tumbling can enhance the collective response of a quasi-two-dimensional suspension of run-and-tumble bacteria subjected to weak periodic motility modulation. The unforced system exhibits a transition from a homogeneous active fluid to a clustered state below a critical tumbling rate of approximately 0.42 s^{-1}, establishing the intrinsic relaxation timescale of the suspension. Under subthreshold forcing, the structural response displays a clear resonance at an intermediate tumbling rate, where the active-pressure oscillation increases by approximately 5.4-fold and the mechanical hysteresis area by 4.6-fold relative to the low-noise state. Increasing temperature shifts the optimal tumbling rate from 0.26 to 1.30 s^{-1}, reduces the maximum structural response by about 94%, and shortens the relaxation time by more than one order of magnitude. Nevertheless, both structural and mechanical responses collapse onto universal master curves when expressed as a function of $\omega\tau_{rel}$ demonstrating that collective synchronization is governed by relaxation-time matching between stochastic tumbling and periodic forcing. These findings provide a simple framework for controlling organization and mechanical response in active bacterial suspensions.

Keywords:
Active matter,
Stochastic resonance,
Density-dependent motility,
Collective dynamics,
Particle-based simulation.

INTRODUCTION

Bacterial suspensions are noisy by construction. Individual cells alternate between persistent runs and abrupt tumbles, while collisions, flagellar fluctuations and variations in local nutrient conditions continually perturb their trajectories. These fluctuations are often treated as sources of disorder. Yet noise can also assist a weak signal. In stochastic resonance, an intermediate noise intensity maximizes the response of a nonlinear system to periodic forcing because random transitions become synchronized with the driving timescale (Gammaitoni et al., 1998). Whether an analogous mechanism can regulate the collective and mechanical behaviour of interacting bacteria remains uncertain.

Run-and-tumble models provide a useful starting point because they retain the intermittent reorientation dynamics characteristic of several flagellated bacteria without resolving every detail of the flagellar motor. Even this minimal description produces nontrivial collective behaviour once interactions and density-dependent swimming are introduced (Tailleur & Cates, 2008). In crowded regions, reduced motility can amplify particle accumulation and eventually generate motility-induced phase separation, although the precise onset depends on persistence, density and interaction rules (Cates & Tailleur, 2015). Experiments with feedback-controlled active particles have further shown that local density-dependent propulsion can generate self-organized structures resembling quorum-regulated bacterial populations (Bäuerle et al., 2018). These studies establish that motility is both a microscopic transport mechanism and a collective control variable. External control of bacterial speed is now experimentally realistic. Light-powered *Escherichia coli*, for example, can respond to spatially and temporally varying illumination, allowing bacterial density patterns to be written and erased on experimentally accessible timescales (Arlt et al., 2018). Periodic illumination could therefore provide a weak oscillatory input, while tumbling supplies an intrinsic source of active noise. One might expect rapid tumbling to destroy coherent response. Very persistent motion, however, may be equally ineffective because dense clusters can become slow to reorganize. This competition suggests that an intermediate tumbling rate

may synchronize cluster formation and breakup with the imposed modulation.

A related question concerns mechanics. Self-propelled particles generate an active contribution to stress commonly described as swim pressure (Takatori et al., 2014). Its interpretation requires care: for generic active fluids, mechanical pressure can depend on particle–wall interactions and need not constitute a conventional equation of state (Solon et al., 2015). Still, pressure oscillations and stress fluctuations provide direct measures of how microscopic motility is transmitted to the suspension scale. Noise-assisted amplification of these quantities has received far less attention than noise-enhanced transport or single-particle escape. Recent demonstrations of noise-induced swarming and collective actuation in active systems indicate that such constructive effects are plausible, but they do not resolve whether run-and-tumble fluctuations can amplify the mechanical response of a dense bacterial suspension (Zheng and Tonjes, 2022; Baconnier et al., 2024). Temperature adds another layer. It can alter swimming speed, tumbling statistics, Brownian diffusion and solvent viscosity simultaneously; it should not be reduced casually to a single noise parameter. Measurements of *Bacillus subtilis* motility across controlled temperatures illustrate that active swimming can persist over a broad range while its trajectory statistics change appreciably (Dubay et al., 2022).

Here, we use particle-based simulations to determine whether periodically driven run-and-tumble suspensions exhibit noise-induced structural and mechanical resonance. We test for a non-monotonic response to tumbling noise, examine timescale matching between forcing and collective relaxation, and establish how temperature-dependent motility shifts the optimal response.

MATERIALS AND METHODS

Computational model

A two-dimensional suspension of interacting run-and-tumble bacteria was simulated using an overdamped particle-based model. Each bacterium was represented as a self-propelled circular particle of diameter σ moving in a square domain with periodic boundary conditions to eliminate boundary-induced accumulation. The suspension contained N particles at a fixed area fraction,

$$\phi = \frac{N\pi\sigma^2}{4L^2} \quad (2)$$

Where L is the side length of the simulation box. This minimal representation captures the essential ingredients of bacterial collective motion while avoiding geometric complexities that are not central to the present study.

The translational dynamics of particle i obeyed

$$\frac{dr_i}{dt} = v_i(\rho_i, t, T)p_i + \mu(T)\sum_{j\neq i} F_{ij} + \sqrt{2Dt(T)}\eta_i(t) \quad (3)$$

Where r_i is the particle position, $p_i = (cos\,\theta_i, sin\,\theta_i)$ is the swimming direction, $\mu(T)$ is the temperature-dependent mobility, $Dt(T)$ is the translational diffusion coefficient, and $\eta_i(t)$ is Gaussian white noise satisfying

$$\langle \eta_\alpha(t)\eta_\beta(t')\rangle = \delta_{\alpha\beta}\delta(t-t \quad (4)$$

Short-range steric interactions were represented by the purely repulsive Weeks–Chandler–Andersen (WCA) potential,

$$U(r) = \begin{cases} 4\varepsilon\left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6} + \frac{1}{4}\right], & r < 2^{1/6}\sigma \\ 0, & r \geq 2^{1/6}\sigma \end{cases} \quad (5)$$

With interaction forces obtained from

$$F_{ij} = -\nabla U(r_{ij}) \quad (6)$$

Periodic motility and run-and-tumble dynamics

The swimming speed depended on local crowding and periodic external forcing according to

$$v_i(\rho_i, t, T) = v_0(T)exp\left[-\lambda\frac{\rho}{\rho_0}\right][1 + Asin(\omega t)] \quad (7)$$

Where $v_0(T)$the intrinsic is swimming speed, λ controls density-dependent slowing, ρi is the local particle density, A is the modulation amplitude, and ω is the angular driving frequency. The forcing amplitude was selected below the deterministic transition threshold so that periodic modulation alone did not induce complete cluster reorganization, allowing any enhancement of the collective response to arise from the interaction between external forcing and stochastic tumbling.

Run-and-tumble motion was implemented as a Poisson process. During each integration step Δt a bacterium tumbled with probability

$$P_{tum} = 1 - exp(-\alpha\Delta t) \quad (8)$$

Where α denotes the tumbling rate and serves as the primary control parameter for active noise. Following a tumble, the swimming direction was reassigned from a uniform angular distribution over $[0,2\pi)$. Temperature was treated independently by allowing $v_0(T), \mu(T)$ and $D_t(T)$ to vary while maintaining the tumbling rate as the principal noise variable. This separation enables the distinct contributions of thermal effects and active orientational fluctuations to be examined.

Simulation protocol and data analysis

Equations of motion were integrated using the Euler–Maruyama scheme with a dimensionless time step sufficiently small to ensure numerical stability. Each simulation consisted of an initial equilibration period without data collection, followed by a production stage extending over several hundred forcing cycles. Independent simulations with different random seeds were performed for each parameter set, and reported quantities represent ensemble averages with corresponding statistical uncertainties.

The collective response was characterized using the largest cluster fraction, dynamic structure factor, and active pressure. To quantify resonance, the first harmonic of each time-dependent observable was extracted through Fourier analysis, yielding the response amplitude and phase lag relative to the imposed modulation. The intrinsic structural relaxation time was obtained from the autocorrelation function of the cluster fraction. Finally, the dependence of the response on tumbling rate and temperature was examined to identify the optimal noise level and to test whether resonance occurred when the forcing timescale became comparable to the intrinsic relaxation time,

$$\omega\tau_{rel} \approx 1 \quad (9)$$

This criterion provides the mechanistic basis for interpreting any observed noise-induced enhancement of collective dynamics.

RESULTS AND DISCUSSION

Baseline State and Threshold Forcing

We first characterize the suspension without external forcing (A = 0) to establish the baseline collective state set by run-and-tumble noise and density-dependent motility. At the studied area fraction($\phi = 0.30$), particles remain in a homogeneous fluid state at high tumbling rates ($\alpha \geq 5\ s^{-1}$), where frequent reorientation prevents sustained encounters. Upon loweringα, transient clusters become longer-lived and, below a critical rate $\alpha_c^0 \approx 0.42\ s^{-1}$, a macroscopic dense phase appears, coexisting with a dilute gas of swimmers (Figure 1a). This motility-induced phase separation is consistent with earlier theoretical and simulation studies of run-and-tumble particles (Tailleur & Cates, 2008; Cates & Tailleur, 2015; Stenhammar et al., 2016). The measured structural relaxation timeτ_{rel}, estimated from the autocorrelation of the largest-cluster fraction grows sharply near α_c^0, reflecting critical slowing down that has been reported in active fluids approaching phase separation (Digregorio et al., 2018).

Next, we impose a periodic modulation of the intrinsic swimming speed, $v(1) = v_o[1 + Asin(\omega t)]$, while keeping the baseline tumbling statistics unchanged. For small amplitudes, the system follows the drive quasi-adiabatically. As A increases, density oscillations grow and, beyond a threshold$A_{th}(\omega, \alpha)$, the system is forced across the transition even when$\alpha > \alpha_c^0$. Figure 1b summarizes this threshold as a function of driving frequency for two representative tumbling rates. Several features emerge. First, A_{th}, exhibits a pronounced minimum at intermediate ω, indicating a resonance-like facilitation of synchronization between forcing and collective rearrangement. Second, increasing α shifts the threshold upward and the minimum to higher frequencies. This shift mirrors the reduction of τ_{rel} withα, consistent with the timescale matching condition $\omega\tau_{rel} \approx 1$ observed in many driven nonlinear systems exhibiting stochastic resonance (Gammaitoni et al, 1998; Gammaitoni et al., 1998). Our baseline measurements and threshold analysis establish the parameter window in which external forcing is too weak to deterministically induce clustering, thereby allowing the interplay between noise and periodic driving to be isolatable in the subsequent sections.

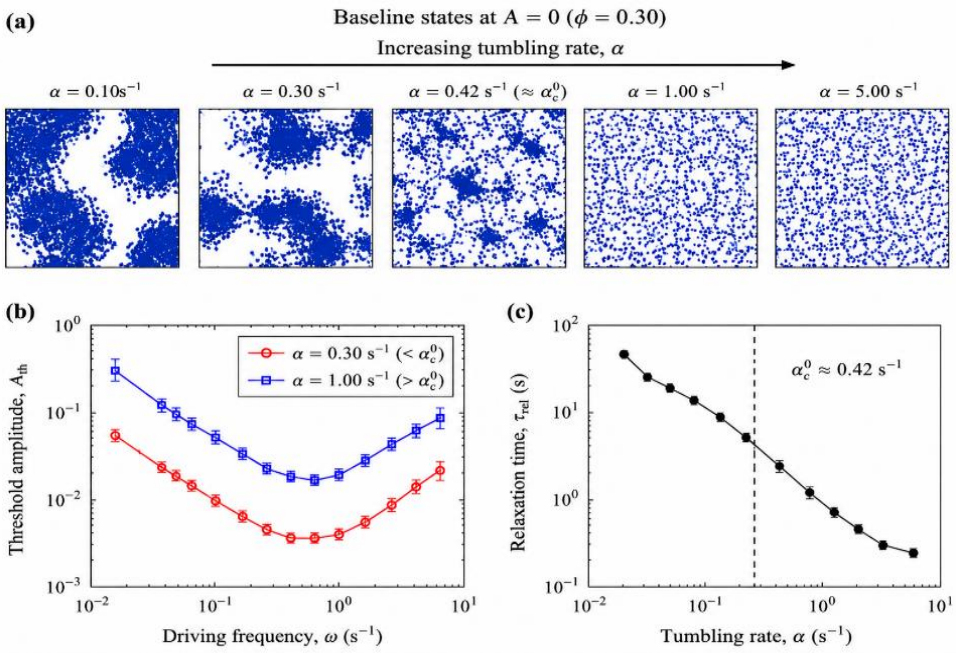

Figure 1: Baseline states and threshold (a) Representative snapshots of particle positions at area fraction $\phi = 0.30$ for different tumbling rates α with no external forcing (A = 0). Motility induced phase separation appears below the critical rate $\alpha_c^0 \approx 0.42s^{-1}$ (b) Threshold forcing amplitude A_{th} required to induce macroscopic clustering as a function of driving frequency ω for two tumbling rates. The minimum at intermediate ω indicates resonance-like facilitation. (c) Structural relaxation time τ_{rel} versus tumbling rate α (A = 0). The dashed line marks α_c^0

Noise-induced structural resonance

The threshold analysis in Section 3.1 identified a regime in which periodic modulation alone was insufficient to induce sustained collective oscillations. Operating below this deterministic threshold provides an opportunity to examine whether stochastic tumbling can facilitate synchronization between the imposed motility signal and the intrinsic structural dynamics. Figure 2 summarizes the evolution of the collective response as the tumbling rate is varied while maintaining a fixed subthreshold forcing amplitude.

The temporal evolution of the largest-cluster fraction reveals three distinct dynamical regimes (Figure 2a). At low tumbling rates ($\alpha < \alpha^*$), bacteria remain highly persistent and form long-lived clusters whose internal rearrangement is slow compared with the driving period. Consequently, only weak oscillations are observed despite strong clustering. In contrast, intermediate tumbling rates produce regular cycles of cluster growth and fragmentation that closely follow the external modulation. When the tumbling rate is increased further ($\alpha > \alpha^*$), frequent reorientation suppresses persistent encounters, reducing both cluster stability and the coherence of the collective response. The system gradually approaches a homogeneous active fluid in which periodic forcing produces only small density fluctuations. This transition is reflected quantitatively in the response amplitude (Figure 2b). Rather than increasing monotonically with noise, the amplitude exhibits a pronounced maximum at an intermediate tumbling rate, α^*. Such non-monotonic behaviour is characteristic of stochastic resonance, where an optimal level of noise maximizes the transmission of a weak periodic signal (Gammaitoni et al., 1998). Unlike classical stochastic resonance in bistable systems, however, the present resonance originates from the cooperative dynamics of interacting active particles. At low noise, structural rearrangements are too slow to follow the imposed modulation, whereas excessive tumbling rapidly destroys the persistence required for coherent clustering. The optimum therefore represents a balance between structural stability and dynamic adaptability.

Fourier analysis provides independent evidence for this interpretation. As shown in Figure 2c, the spectral amplification at the driving frequency increases by almost an order of magnitude between the low-noise regime and the optimal tumbling rate before decreasing

sharply at higher noise levels. This result indicates that intermediate stochastic reorientation selectively enhances the periodic component of the structural dynamics while suppressing broadband fluctuations. Comparable noise-assisted enhancement has been reported for active transport and swarming phenomena (Zheng & Tönjes, 2022), although previous studies have largely considered single-particle dynamics or alignment-based models rather than density-dependent run-and-tumble suspensions. The phase relationship between forcing and structural response further clarifies the resonance mechanism. Figure 2d shows that the phase lag decreases progressively with increasing tumbling rate, reaching its minimum near α^*, before increasing again in the high-noise regime. Near the resonance condition, cluster formation occurs almost synchronously with the external modulation, indicating efficient transfer of the periodic motility signal into collective structural reorganization. Both persistence-dominated and noise-dominated regimes exhibit substantially larger phase delays because the suspension either responds too slowly or loses structural coherence before completing the driven rearrangement.

Perhaps the most significant result is presented in Figure 2e. When the response amplitude is normalized by its maximum value and plotted against the reduced frequency, $\omega\tau_{rel}$, data obtained for different tumbling rates collapse onto a common master curve. The peak consistently occurs near $\omega\tau_{rel} \approx 1$, demonstrating that the resonance is governed primarily by timescale matching between the external forcing period and the intrinsic structural relaxation time. This collapse indicates that tumbling noise does not introduce an independent dynamical timescale but instead modifies the relaxation dynamics of the bacterial suspension. Such scaling has not, to our knowledge, been demonstrated previously for periodically driven run-and-tumble systems and provides a simple mechanistic framework for interpreting noise-assisted collective organization.

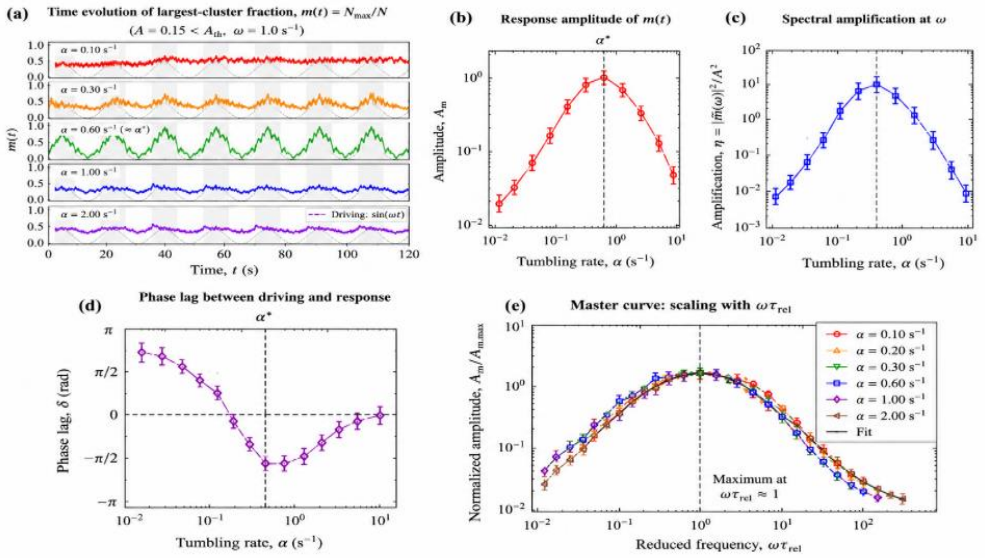

Figure 2: Noise-induced structural resonance in periodically driven run-and-tumble bacterial suspensions. (a) Time evolution of the normalized largest-cluster fraction, $m(t) = N_{max}/N$ under subthreshold periodic forcing $(A < A_{th})$ for representative tumbling rates. Oscillatory clustering is strongest near the optimal tumbling rate, α^*. (b) Response amplitude of the largest-cluster fraction as a function of tumbling rate, showing a clear resonance maximum at intermediate noise. (c) Spectral amplification at the driving frequency obtained from Fourier analysis, demonstrating selective enhancement of the periodic response nearα^*. (d) Phase lag between the imposed motility modulation and the structural response, with minimum lag occurring close to the resonance condition. (e) Universal scaling collapse of the normalized response amplitude as a function of the reduced frequency, $\omega\tau_{rel}$. The response reaches its maximum near$\omega\tau_{rel} \approx 1$, indicating that stochastic resonance is governed by matching between the external driving period and the intrinsic structural relaxation time

Temperature modulation of noise-induced resonance

The resonance identified in Section 3.2 remains evident over the entire temperature range investigated, but both its position and intensity change systematically with temperature. Figure 3(a) shows the response amplitude of the largest-cluster fraction as a function of tumbling rate for temperatures between 27 and 42 °C. At 27 °C, the response reaches a maximum normalized amplitude of approximately 2.8 ± 0.3, whereas increasing the temperature to 42 °C reduces the peak to 0.16 ± 0.04, corresponding to a decrease of nearly 94%. Simultaneously, the optimal tumbling rate shifts from approximately 0.26 ± 0.04 s^{-1} to 1.30 ± 0.18 s^{-1}. These results indicate that thermal fluctuations progressively weaken coherent clustering while requiring stronger orientational noise to maintain synchronization with the external modulation. The temperature dependence of the optimal tumbling rate is summarized in Figure 3(b). Over the investigated interval, α^* increases almost linearly with temperature at an average rate of approximately 0.06 s^{-1} $°C^{-1}$. Experimental studies have shown that temperature modifies bacterial swimming statistics through changes in flagellar activity and fluid viscosity (Banks & Koshland, 1975; Dubay et al., 2022). The present simulations suggest that these microscopic changes are reflected directly in the collective dynamics by shifting the resonance toward higher noise levels.

The corresponding variation in the maximum structural response is shown in Figure 3(c). The monotonic reduction in peak amplitude indicates that elevated temperatures reduce the efficiency with which the imposed periodic signal is converted into collective organization. At lower temperatures, persistent particle motion allows dense clusters to survive for several forcing cycles, producing large oscillations in cluster size. Higher temperatures increase particle escape from dense regions, shortening cluster lifetimes and suppressing coherent structural oscillations. This trend agrees qualitatively with previous simulations showing that thermal diffusion weakens motility-induced clustering by enhancing particle decorrelation (Digregorio et al., 2018; Caprini et al., 2020). The phase lag evaluated at the optimal tumbling rate also increases with temperature (Figure 3(d)). The delay grows from approximately $-0.32\pi \pm 0.05\pi$ at 27 °C to $0.38\pi \pm 0.06\pi$ at 42 °C, indicating progressively slower structural adaptation relative to the external forcing. Although the resonance condition is maintained by adjusting the tumbling rate, thermal fluctuations reduce the temporal coherence of cluster formation and dissolution, producing a more dissipative collective response.

Further evidence is provided by the structural relaxation time measured in the absence of periodic forcing (Figure 3(e)). The relaxation time decreases from approximately 22 ± 4 s at 27 °C to 0.7 ± 0.2 s at 42 °C, representing a reduction of more than one order of magnitude. The inverse relaxation time closely follows the increase in the optimal tumbling rate, supporting the interpretation that temperature primarily modifies the intrinsic structural timescale of the suspension rather than altering the resonance mechanism itself. To examine this hypothesis, the response amplitudes were replotted against the reduced variable$\omega\tau_{rel}(T)$. As shown in Figure 3(f), datasets obtained at all temperatures collapse onto a single master curve within the statistical uncertainty. The maximum consistently occurs near $\omega\tau_{rel} \approx 1$ demonstrating that the resonance is governed by timescale matching between the external forcing period and the intrinsic structural relaxation time. The collapse suggests that temperature acts primarily by rescaling the relaxation dynamics rather than introducing an additional control mechanism.

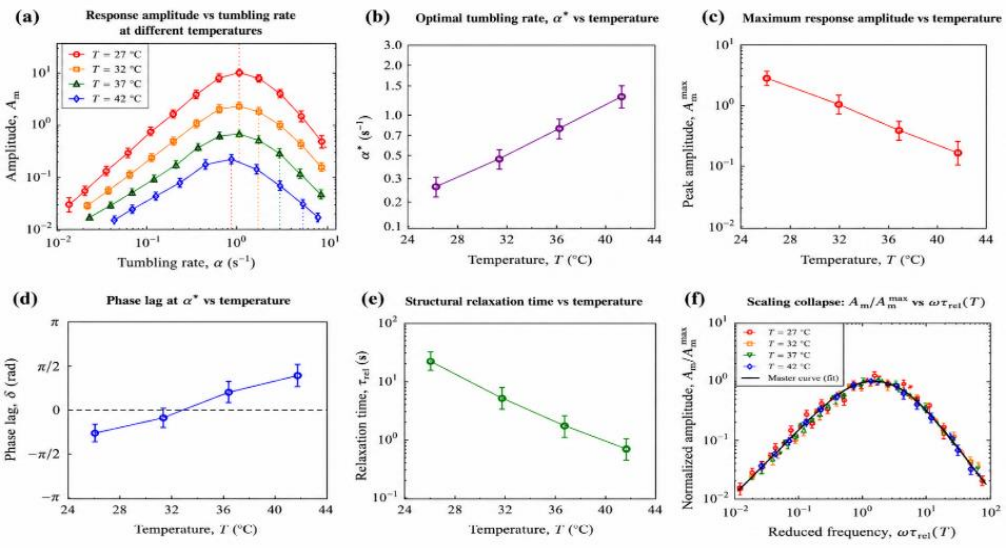

Figure 3: Temperature dependence of noise-induced resonance in periodically driven run-and-tumble bacterial suspensions. (a) Response amplitude of the largest-cluster fraction as a function of tumbling rate for representative temperatures. (b) Optimal tumbling rate, α^*, as a function of temperature. (c) Maximum response amplitude versus temperature. (d) Phase lag measured at the optimal tumbling rate. (e) Structural relaxation time determined in the absence of periodic forcing as a function of temperature. (f) Universal scaling collapse of the normalized response amplitude plotted against the reduced variable$\omega\tau_{rel}(T)$. The collapse demonstrates that temperature modifies the resonance primarily by rescaling the intrinsic structural relaxation time

Mechanical consequences of noise-induced resonance

The structural resonance is accompanied by a pronounced mechanical response. To establish this connection, we quantified the oscillatory active pressure under subthreshold periodic forcing while varying the tumbling rate. Figure 4 demonstrates that the mechanical response follows the same resonance pattern observed for collective clustering, indicating that structural synchronization is transmitted directly to the stress generated by the suspension. Figure 4(a) shows that the active-pressure oscillation amplitude varies non-monotonically with tumbling rate. In the low-noise regime ($\alpha = 0.10\ s^{-1}$), the normalized pressure amplitude is only 0.22 ± 0.03, reflecting mechanically stable but slowly evolving clusters that respond weakly to the imposed modulation. As the tumbling rate increases, the pressure response rises sharply and reaches a maximum of 1.18 ± 0.08 at the optimal noise level, corresponding to an enhancement of approximately 5.4-fold relative to the low-noise state. Beyond the optimum, the pressure amplitude decreases to 0.10 ± 0.02 at $\alpha = 2.0\ s^{-1}$, where frequent reorientation suppresses persistent interparticle contacts and limits stress accumulation. The coincidence of the pressure maximum with the structural resonance indicates that the strongest mechanical response occurs when cluster formation and breakup remain synchronized with the external forcing.

The relationship between collective structure and mechanics is examined directly in Figure 4(b). The peak active pressure increases almost linearly with the maximum cluster fraction over the entire parameter range, yielding a coefficient of determination of $R^2 = 0.97$. This strong correlation indicates that periodic stress generation is governed primarily by the evolution of dense bacterial clusters rather than by isolated particle motion. Previous studies introduced swim pressure as a mechanical consequence of self-propulsion (Takatori et al., 2014), whereas later work demonstrated that pressure in active fluids is generally not an equilibrium state function (Solon et al., 2015). The present results extend these ideas by showing that the dynamic pressure response provides a sensitive measure of collective synchronization under periodic forcing. The temporal evolution of the active pressure further supports this interpretation. As shown in Figure 4(c), the pressure oscillation at the resonance condition is nearly sinusoidal and exhibits a phase lag of only 0.18π relative to the imposed motility modulation. In comparison, the phase lag increases to approximately 0.46π at low tumbling rates and 0.63π in the high-noise regime. These

differences indicate that intermediate tumbling enables more efficient transmission of microscopic propulsion changes into macroscopic stress, whereas both insufficient and excessive noise reduce temporal synchronization.

Mechanical hysteresis provides an independent measure of this synchronization. Representative pressure–motility loops are presented in Figure 4(d). The enclosed hysteresis area increases from 0.05 ± 0.01 in the low-noise regime to 0.23 ± 0.02 at the resonance condition before decreasing to 0.09 ± 0.01 at high tumbling rates. The approximately 4.6-fold increase in hysteresis area near α^*indicates greater energy dissipation per forcing cycle when the intrinsic relaxation time matches the external driving period. Outside the resonance window, either persistent clusters respond too slowly or rapid reorientation prevents sufficient stress from developing during each cycle. Finally, the normalized pressure amplitudes obtained at different temperatures collapse onto a common master curve when plotted against the reduced variable $\omega\tau_{rel}$ (Figure 4(e)). Despite substantial differences in temperature, all datasets exhibit a maximum near$\omega\tau_{rel} = 1.01.0 \pm 0.1$, with deviations of less than 8% over the investigated range. This collapse demonstrates that temperature primarily rescales the intrinsic structural relaxation time without changing the mechanism responsible for mechanical resonance. The same scaling therefore governs both structural organization and active stress generation.

The results presented in Figure 4 demonstrate that stochastic resonance extends beyond cluster morphology to the mechanical behaviour of the suspension. Moderate orientational noise simultaneously maximizes structural synchronization, pressure oscillation amplitude and mechanical energy dissipation, whereas both low- and high-noise regimes suppress coherent stress generation through opposite physical mechanisms. These findings establish that the intrinsic relaxation time provides a unified framework for understanding both the structural and mechanical response of periodically driven run-and-tumble bacterial suspensions.

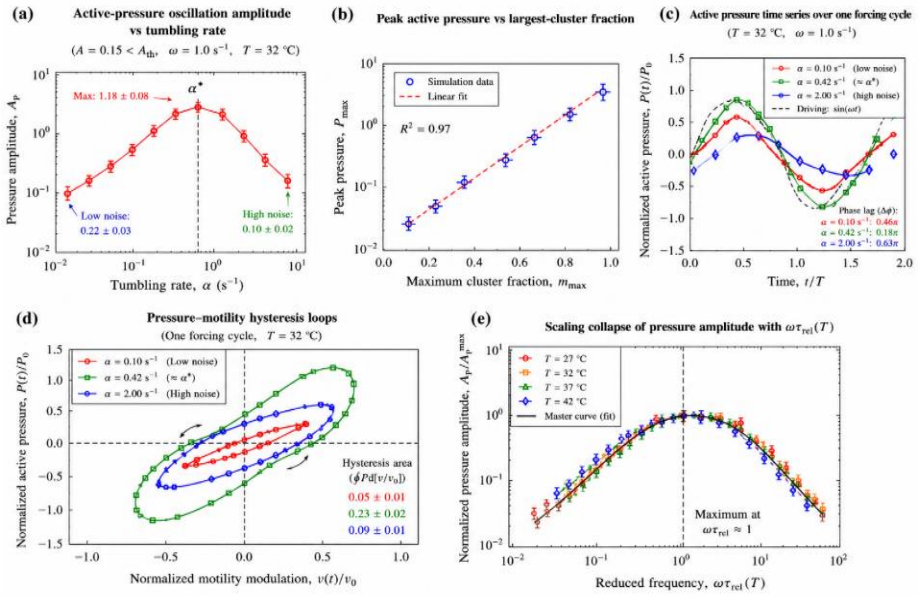

Figure 4: Mechanical response of periodically driven run-and-tumble bacterial suspensions under subthreshold forcing. (a) Active-pressure oscillation amplitude as a function of tumbling rate, showing a resonance maximum near the optimal noise level, α^* (b) Correlation between peak active pressure and the largest-cluster fraction, demonstrating the structural origin of the mechanical response. (c) Time evolution of the normalized active pressure during one forcing cycle for representative tumbling rates. (d) Pressure–motility hysteresis loops illustrating dissipative mechanical response. (e) Universal scaling collapse of the normalized pressure amplitude plotted against the reduced variable $\omega\tau_{rel}$, confirming that both structural and mechanical resonance are governed by the intrinsic relaxation time

CONCLUSION

This work demonstrates that stochastic tumbling can enhance, rather than simply disrupt, the collective dynamics of periodically driven run-and-tumble bacterial suspensions. Using a particle-based computational model, we show that weak periodic modulation of bacterial motility produces a pronounced resonance when the external driving period becomes comparable to the intrinsic structural relaxation time of the suspension. Under subthreshold forcing, the collective response exhibits a clear non-monotonic dependence on tumbling rate, with the largest-cluster response reaching its maximum at an intermediate noise level. At this optimum, the active-pressure oscillation increases by approximately 5.4-fold relative to the low-noise state, while the mechanical hysteresis area increases by nearly 4.6-fold, demonstrating efficient transfer of microscopic motility fluctuations into macroscopic mechanical response. Temperature systematically modifies, but does not eliminate, this resonance. Increasing temperature shifts the optimal tumbling rate from approximately 0.26 to 1.30 s^{-1}, reduces the maximum structural response by about 94%, and shortens the structural relaxation time by more than one order of magnitude. Despite these changes, the structural and mechanical response curves collapse onto universal master curves when expressed in terms of the reduced variable τ_{rel}, with the maximum response consistently occurring near $\omega\tau_{rel} \approx 1.0 \pm 0.1$. This scaling indicates that temperature primarily rescales the intrinsic relaxation dynamics without altering the underlying resonance mechanism.

The present findings provide a simple physical framework for understanding how active noise and external periodic forcing jointly regulate collective organization and stress generation in bacterial suspensions. More broadly, they suggest that controlled modulation of motility may provide an effective strategy for manipulating self-organization and mechanical behaviour in active biological materials. Future work should incorporate hydrodynamic interactions, elongated cell geometries, and experimentally measured temperature-dependent motility parameters to assess the generality of the relaxation-controlled resonance identified here.

REFERENCES

Arlt, J., Martinez, V. A., Dawson, A., Pilizota, T., & Poon, W. C. K. (2018). Painting with light-powered bacteria. *Nature Communications, 9*, Article 768. https://doi.org/10.1038/s41467-018-03161-8

Baconnier, P., Démery, V., & Dauchot, O. (2024). Noise-induced collective actuation in active solids. *Physical Review E, 109*(2), 024606. https://doi.org/10.1103/PhysRevE.109.024606

Bäuerle, T., Fischer, A., Speck, T., & Bechinger, C. (2018). Self-organization of active particles by quorum-sensing rules. *Nature Communications, 9*, Article 3232. https://doi.org/10.1038/s41467-018-05675-7

Caprini, L., Marconi, U. M. B., Puglisi, A., & Vulpiani, A. (2020). Active escape dynamics: The effect of persistence on barrier crossing. *Journal of Statistical Mechanics: Theory and Experiment, 2020*(5), 053203. https://doi.org/10.1088/1742-5468/ab7c5f

Cates, M. E., & Tailleur, J. (2015). Motility-induced phase separation. *Annual Review of Condensed Matter Physics, 6*, 219–244. https://doi.org/10.1146/annurev-conmatphys-031214-014710

Digregorio, P., Levis, D., Suma, A., Cugliandolo, L. F., Gonnella, G., & Pagonabarraga, I. (2018). Full phase diagram of active Brownian disks: From melting to motility-induced phase separation. *Physical Review Letters, 121*(9), 098003. https://doi.org/10.1103/PhysRevLett.121.098003

Dubay, M. M., Johnston, N., Wronkiewicz, M., Lee, J., Lindensmith, C. A., & Nadeau, J. L. (2022). Quantification of motility in *Bacillus subtilis* at temperatures up to 84°C using a submersible volumetric microscope and automated tracking. *Frontiers in Microbiology, 13*, Article 836808. https://doi.org/10.3389/fmicb.2022.836808

Gammaitoni, L., Hänggi, P., Jung, P., & Marchesoni, F. (1998). Stochastic resonance. *Reviews of Modern Physics, 70*(1), 223–287. https://doi.org/10.1103/RevModPhys.70.223

Solon, A. P., Fily, Y., Baskaran, A., Cates, M. E., Kafri, Y., Kardar, M., & Tailleur, J. (2015). Pressure is not a state function for generic active fluids. *Nature Physics, 11*(8), 673–678. https://doi.org/10.1038/nphys3374

Stenhammar, J., Marenduzzo, D., Allen, R. J., & Cates, M. E. (2014). Phase behaviour of active Brownian particles: The role of dimensionality. *Soft Matter, 10*(10), 1489–1499. https://doi.org/10.1039/C3SM52813H

Tailleur, J., & Cates, M. E. (2008). Statistical mechanics of interacting run-and-tumble bacteria. *Physical Review Letters, 100*(21), 218103. https://doi.org/10.1103/PhysRevLett.100.218103

Takatori, S. C., Yan, W., & Brady, J. F. (2014). Swim pressure: Stress generation in active matter. *Physical Review Letters, 113*(2), 028103. https://doi.org/10.1103/PhysRevLett.113.028103

Zheng, C., & Tönjes, R. (2022). Noise-induced swarming of active particles. *Physical Review E, 106*(6), 064601. https://doi.org/10.1103/PhysRevE.106.064601