

Many-body colloidal dynamics under stochastic resetting: Competing effects of particle interactions on the steady-state distribution

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The random arrest of the diffusion of a single particle and its return to its origin has served as the paradigmatic example of a large variety of processes undergoing stochastic resetting. While the implications and applications of stochastic resetting for a single particle are well understood, less is known about the resetting of many interacting particles. In this study, we experimentally and numerically investigate a system of six colloidal particles undergoing two types of stochastic resetting protocols: global resetting, where all particles are returned to their origin simultaneously, and local resetting, where particles are reset one at a time. Our particles interact mainly through hard-core repulsion and hydrodynamic flows. We find that the most substantial effect of interparticle interactions is observed for local resetting, specifically when particles are physically dragged to the origin. In this case, hard-core repulsion broadens the steady-state distribution, while hydrodynamic interactions significantly narrow the distribution. The combination results in a steady-state distribution that is wider compared to that of a single-particle system for both global and local resetting protocols.

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Introduction. Stochastic resetting (SR), the abrupt restarting of a process at random time intervals, drives the system toward a steady state. When applied to a diffusing particle, it leads to the emergence of a stationary density profile [1–3]. SR-induced steady states have been used to model a wide range of physical and natural phenomena [2,4,5], including the height distribution of fluctuating interfaces [6,7] and the mechanisms governing cell division [8].

For exponentially distributed resetting times at a constant rate, the steady-state density follows a Laplacian form, determined by the ratio of the resetting rate to the diffusion coefficient [1]. This density profile, however, changes when the resetting time distribution is altered [9] or when partial resets are introduced [10–12]. Further complexity arises when memory effects or ballistic motion are incorporated into SR processes [13,14], or if multiplicative noise is concerned [15]. The ability to control and engineer steady-state profiles through SR opens up potential applications, such as accelerating state transitions [16].

While understanding SR in single-particle systems provides a foundation, its impact on multiparticle systems is crucial for addressing real-world conditions. Numerous phenomena, including reaction kinetics [17,18], foraging [19–21], and queuing [22], inherently involve interacting processes. Pioneering studies on many-body systems under SR [5,23,24] define global and local resetting protocols. The for-

mer refers to a process in which the entire system is reset at each resetting event. In contrast, only one of the particles is returned to the origin at each resetting event in the latter. These protocols can lead to significant differences in the emergent steady state. For instance, in a system of particles diffusing on a ring [23], these two protocols resulted in qualitative differences in the evolving steady-state distribution of the particle distribution. Interestingly, resetting only a small subset of coupled oscillators can lead to full system synchronization [25]. Global resetting results in strong correlations between the particles and drives the system into a nonequilibrium steady state with long-range interactions that emerge purely from the dynamics [24,26].

When comparing the extreme edges of the distributions for a large number of particles, $N \gg 1$, diffusing on a line under resetting, global resetting yields a system radius with a typical value scaling as $\sim \sqrt{\ln N}$ [27]. In contrast, local resetting reproduces the same $\sqrt{\ln N}$ scaling when a randomly chosen particle is reset, but leads to a system radius that becomes independent of N when the farthest particle is selectively reset [28].

The analytical treatment of stochastic resetting in complex many-body systems is challenging due to the coupled and nonlinear dynamics from interparticle interactions like hard-core repulsion and long-range hydrodynamic coupling. Experimental studies are crucial for understanding how these interactions affect system behavior under stochastic resetting, yet controlled experiments in this area are limited. Our previous work showed that the renewal approach successfully predicts steady states for global and instantaneous resetting using unperturbed suspension dynamics [29]. However, the instantaneous nature of these returns suppressed interaction effects, preventing a full understanding of interparticle coupling's influence on resetting. Therefore, more experimental

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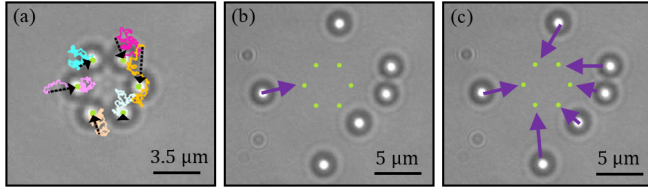


FIG. 1. Colloidal particles under stochastic resetting to a hexagonal configuration using automated holographic optical tweezers. (a) Particles trapped in their initial arrangement with trajectory segments between resetting events superimposed. Green dots indicate the positions of the optical traps, and black dashed lines indicate the return routes. Two resetting protocols are illustrated: (b) local resetting and (c) global resetting protocols. Purple arrows indicate particle movement during a reset.

studies with finite return times are necessary to investigate the significant role of these interactions.

In this Letter, we present an experimental and numerical investigation into the impact of realistic interparticle interactions on steady-state distributions arising from stochastic resetting. We employ optical trapping techniques to experimentally reset colloidal particles suspended in water. Initially, we measure the free propagator of a particle within a many-body system and quantify how interparticle interactions alter its shape relative to the single-particle case. Subsequently, we investigate the effect of these interactions on the steady-state distribution under various resetting protocols. Through numerical analysis, we differentiate between the contributions of distinct interaction types and uncover competing influences on the evolution of the steady-state distribution. Finally, we demonstrate that the specific impact of each interaction strongly depends on the chosen resetting protocol.

Specifically, our experiments are conducted using holographic optical tweezers (HOTs) [30,31] to manipulate the positions of charge-stabilized silica colloidal particles (Polysciences; diameter $d = 1.5 \pm 0.08 \mu\text{m}$, density $\rho = 2 \text{ g/cm}^3$), which are suspended slightly above a glass sample floor ($\sim 0.25 \mu\text{m}$) due to a balance between gravity, electrostatic repulsion, and thermal forces. The particles primarily interact through partially suppressed hydrodynamic interactions [32–34] and near hard-core repulsion [35–37]. At the start of each experiment, particles are optically trapped in a hexagonal configuration around the origin, with an intertrap distance of $R_0 = 2.5 \pm 0.03 \mu\text{m}$. The particles are then released and are allowed to diffuse freely [Fig. 1(a)].

An automated computer protocol manages the resetting process, beginning by randomly selecting the time for the next reset event from an exponential distribution with an average resetting rate r . When this time arrives, the system captures an image of the sample. Using conventional image analysis [38], all the particles locations are extracted. The protocol then projects optical traps onto the particles designated for resetting. A sequence of partially overlapping trap displacements guides each selected particle back to its original position in the hexagonal configuration (see video in the Supplemental Material [39]). After successfully resetting all designated particles, the optical traps are deactivated, releasing the particles. The countdown for the next reset event starts immediately. To

enable a direct comparison of local and global returns [Figs. 1(b) and 1(c)], both were conducted under an approximately fixed-duration resetting protocol; i.e., the return phase duration is fixed and is independent of the return distance.

To complement our experiments and distinguish between hydrodynamic interactions and hard-core repulsion, we conduct Stokesian dynamics simulations [33,40,41]. Hard-core repulsion is implemented using a repulsive Weeks-Chandler-Anderson pair interaction [42], while hydrodynamic interactions are captured through the many-body Rotne-Prager mobility tensor [43]. Temperature effects are introduced via a Gaussian-distributed random force that adheres to the fluctuation-dissipation relation, utilizing the same mobility tensor.

For a single particle under SR and many-particle systems under global resetting, it is common to treat separately the free diffusion and the return phases of the process [3,44]. In such cases, the contribution of the free diffusion phase to the steady-state distribution can be calculated using the renewal equation,

$$p(x, t|x_0) = e^{-rt} C(x, t|x_0) + r \int_0^t d\tau e^{-r\tau} C(x, \tau|x_0), \quad (1)$$

where r is the resetting rate and $C(x, t|x_0)$ is the probability density of finding a particle at position x at time t , given it started its walk at x_0 , i.e., the reset-free propagator [1]. We note that this separation is impossible for local resetting, in which a particle is returned while other particles continue diffusing.

In the case of normal diffusion, where $C(x, t)$ follows a Gaussian distribution, the well-known steady-state solution is obtained [1]:

$$\rho(x|x_0) = \frac{\alpha_0}{2} \exp(-\alpha_0|x - x_0|), \quad (2)$$

where $\alpha_0 = \sqrt{r/D}$ represents an inverse length scale corresponding to the characteristic distance a particle diffuses between reset events.

Effect of particle interaction on the diffusion propagator. To evaluate the impact of particle interactions on the free diffusion propagator, we begin by tracking the motion of a single particle released from an optical trap and extracting its trajectory using conventional image analysis [38]. This process is repeated 15 000 times, with each release lasting 2 min. Next, we simultaneously released six particles from their respective traps and tracked their motion for the same duration, repeating the experiment 500 times. The experimentally measured free propagator of a single particle is in excellent agreement with the theoretical prediction at both short times ($t = 2 \text{ s}$) and longer times ($t = 20 \text{ s}$), as shown in Fig. 2(a). When comparing the free propagator of the six-particle system to that of a single particle, we find that they coincide at short times, but at longer times, a slight shift of the probability density toward larger distances emerges [Fig. 2(a)].

To quantify the deviation of the single- and six-particle propagators, C_s and C_m , over time, we use the Jensen-Shannon divergence [Fig. 2(b)]. Unlike the Kullback-Leibler divergence, this measure remains well defined even when one of the propagators approaches zero, a common consequence of finite data size. At short times, the divergence remains small

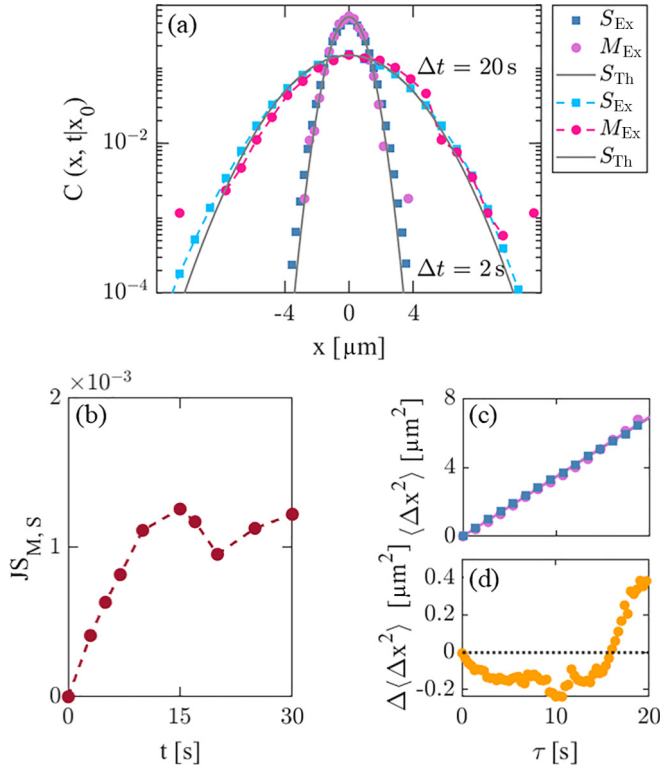


FIG. 2. (a) Reset-Free Propagators $C(x, t|x_0)$ of single- and six-particle systems at $t = 2\text{ s}$ and $t = 20\text{ s}$. Single (six)-particle experimental measurements are presented by blue squares (pink circles), and the normal diffusion Gaussian propagator with $D = 0.18\text{ }\mu\text{m}^2/\text{s}$ is presented by a gray line. (b) The Jensen-Shannon (JS) divergence between single- and six-particle propagators as a function of time. (c) Ensemble average mean square displacement (MSD) as a function of lag time τ of single (blue) and six-particle (pink) systems, and (d) the difference between them.

since the particles have not yet interacted significantly via hard-core repulsion. As time progresses, the divergence increases, reaching a peak at intermediate times when particles come into close proximity, and their interactions become more pronounced, leading to more significant differences between the single-particle and many-body distributions. We expect these differences to emerge on a timescale related to the diffusion time required for particles to traverse their initial separation, which aligns with our findings. At longer times, as the particles disperse and their interactions diminish, the divergence stabilizes due to the reduced influence of hard-core repulsion.

A more detailed comparison of the free propagator's evolution in both systems can be made by examining the temporal evolution of the mean square displacement. For the single-particle system, it follows the expected linear dependence on lag time τ [Fig. 2(c)]. In contrast, the mean square displacement of the six-particle system does not follow a strictly linear dependence on lag time. At short times, it grows more slowly than in the single-particle case, indicating a reduced effective diffusion constant, $D_m = 0.16 \pm 0.03\text{ }\mu\text{m}^2/\text{s}$ compared to $D_s = 0.18 \pm 0.03\text{ }\mu\text{m}^2/\text{s}$. In this regime, before the particles diffuse far enough to collide, they remain relatively close to each other and primarily interact through hydrodynamic

interactions. The higher colloidal density results in a higher effective viscosity [45], reducing the diffusion coefficient. At longer timescales, collisions between colloidal particles facilitate faster spreading, resulting in an increased mean square displacement, as shown in Fig. 2(c).

Steady state under stochastic resetting. We determine the steady-state distribution of particle positions under stochastic resetting by leveraging reset-free diffusion data. This approach allows us to analyze a wide range of resetting conditions using the same set of experiments [29]. Our analysis follows a systematic procedure that applies to single and six-particle systems under global resetting. First, we generate a sequence of random resetting times, $\{t_1, t_2, \dots\}$, drawn from an exponential distribution with a mean resetting rate r . Next, each recorded reset-free trajectory is truncated at its corresponding reset time t_i . These modified trajectories are then seamlessly concatenated, creating an extended sequence representing a system undergoing instantaneous global resetting (teleportation). Finally, we use this constructed sequence to compute the steady-state distribution under the global and instantaneous resetting protocol.

Alternatively, the steady-state distribution under resetting can be evaluated from the measured free propagator by numerically integrating Eq. (1) and taking $t \rightarrow t_{ss}$ [29]:

$$\rho(x|x_0) \approx r \sum_{i=1}^{t_{ss}} \Delta t \Psi(t_i) C(x, t_i|x_0), \quad (3)$$

where $t_{ss} \approx 60\text{ s}$ is the time it takes the system to reach steady state in our system, and $\Psi(t) = \int_t^\infty r e^{-rt} dt$ is the probability of a process to survive without resetting until time t .

For each particle, we compute the steady-state distribution under resetting along the line connecting the center of the hexagon to its initial position. We obtain the final distribution for the six-particle system by averaging over all individual particle distributions. In Fig. 3(a), we compare the steady-state distributions of the single- and six-particle systems. For the single-particle system, the distributions obtained from experiments (symbols), the numerical renewal equation (dashed lines), and Eq. (2) (solid line) show strong agreement. Comparing the single- (blue) and six-particle (pink) steady-state distributions, we observe a transition to an asymmetric steady-state distribution in the six-particle system. This observation aligns with our earlier findings on interaction effects in the free propagator, where collisions enhance spreading at large distances and intermediate times but constrain motion at smaller radii.

The JS distance between the single- and six-particle systems decreases with increasing resetting rates, reaching an approximately constant low value at $r = 0.5\text{ s}^{-1}$ [Fig. 3(b)]. The results clearly indicate that as the resetting rate decreases, the difference between the distributions becomes more pronounced, corresponding to the increased difference in the free propagator over a long period of time. The particles have more opportunities to interact for the lower measured resetting rates, resulting in a more significant difference between the steady-state distribution of the single-particle system and the many-body system.

Although particle interactions alter both the free propagator and the steady-state distribution, their overall impact

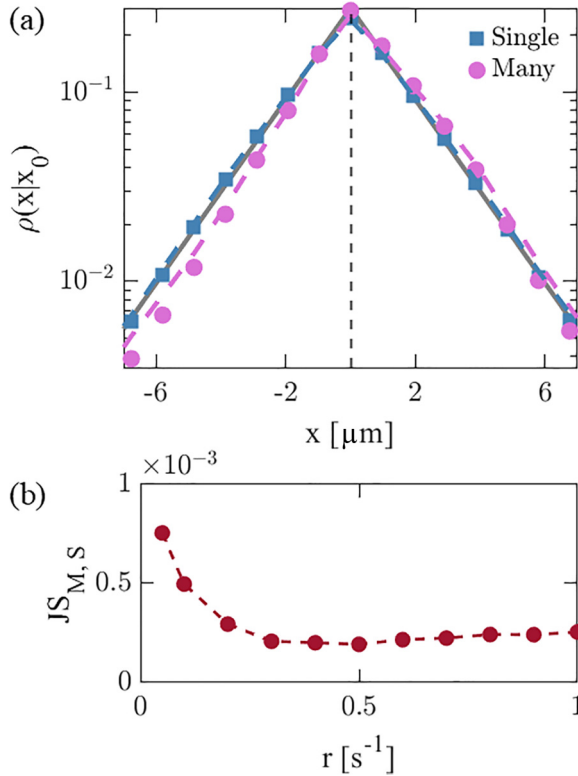


FIG. 3. (a) Steady-State Distributions comparing single- to six-particle systems under a resetting rate of $r = 0.05 \text{ s}^{-1}$. Experimental measurements for single (blue squares) and six (pink circles) particles agree well with the renewal prediction (blue and pink dashed lines, respectively). For the single-particle system, the theoretical prediction according to Eq. (2) is plotted in a solid gray line. (b) The Jensen-Shannon divergence between the steady-state distributions of systems with a single particle (S) and six particles (M).

under global resetting remains limited (Fig. 3). We attribute this to experimental conditions that minimize hydrodynamic interactions and to the idealized protocol of instantaneous returns upon resetting. A more substantial influence of particle interactions is expected if returns involve physically dragging the particle back to the origin in a local resetting scheme, during which other particles continue their diffusive motion.

We implemented a local resetting protocol with constant-time returns, in which particles are actively dragged back to the origin, each at a time, using optical tweezers. As a result, particles can interact with other particles along their return paths. To enable direct comparison with global resetting, we set the local resetting rate to be six times faster than the global resetting rate. In experiments, since returns are performed by a moving laser trap, a diffusing particle that comes close to a resetting particle can also get pulled in by the same laser beam; consequently, both particles end up returning together. We find that approximately 20% of the resetting events, out of 975 recorded, involve multiparticle resets.

We compare the steady-state probability distributions under global and local resetting protocols [Figs. 4(a) and 4(b)]. Under global resetting, particles remain closer to the resetting position, while local resetting leads to broader spatial exploration. This contrast is evident in the azimuthally averaged

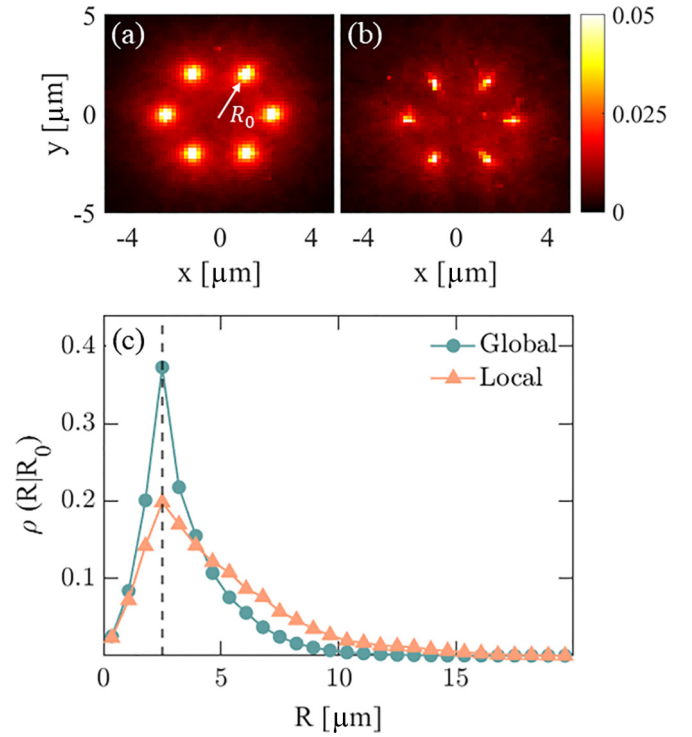


FIG. 4. Experimentally measured two-dimensional six-particle steady-state probability density functions $\rho(x, y)$ under stochastic resetting for global resetting (a) and local resetting (b). A white arrow indicates the mean initial displacement R_0 in our configuration. (c) Experimentally measured radial steady-state distribution for the local resetting (orange triangles) and global resetting (blue circles) protocols. In both cases, the resetting rate is $r = 0.05 \text{ s}^{-1}$, with an average return time of $t_{\text{rn}} = 6.20 \text{ s}$.

distributions [Fig. 4(c)]: Local resetting (orange) results in a significantly broader distribution than global resetting (blue), highlighting the influence of particle interactions in the different resetting protocols.

The resetting protocol we implement starts the clock for the next resetting event only after the returning particle has reached the origin. Consequently, for local resetting, when one particle resets the remaining five continue diffusing, whereas during global resetting each event returns all six particles at once. This difference leads to a longer net diffusing time per particle under local resetting, thereby broadening the steady-state distributions relative to global resetting.

We performed two sets of computer simulations to decouple the contributions of hard-core repulsion and hydrodynamic interactions to the six-particle steady-state distribution. The first included only hard-core repulsion, while the second employed Stokesian dynamics that incorporates hydrodynamic interactions in an idealized, infinite fluid. We also implemented the simulations in such a way that only one particle interacts with the resetting laser at a time, allowing us to avoid spurious multiparticle returns. A further distinction between simulations and experiments is the hydrodynamic interactions: In the experiments, an absorbing boundary alters fluid flow around the particles and weakens their coupling, whereas in the simulations the particles experience stronger, bulklike hydrodynamic interactions.

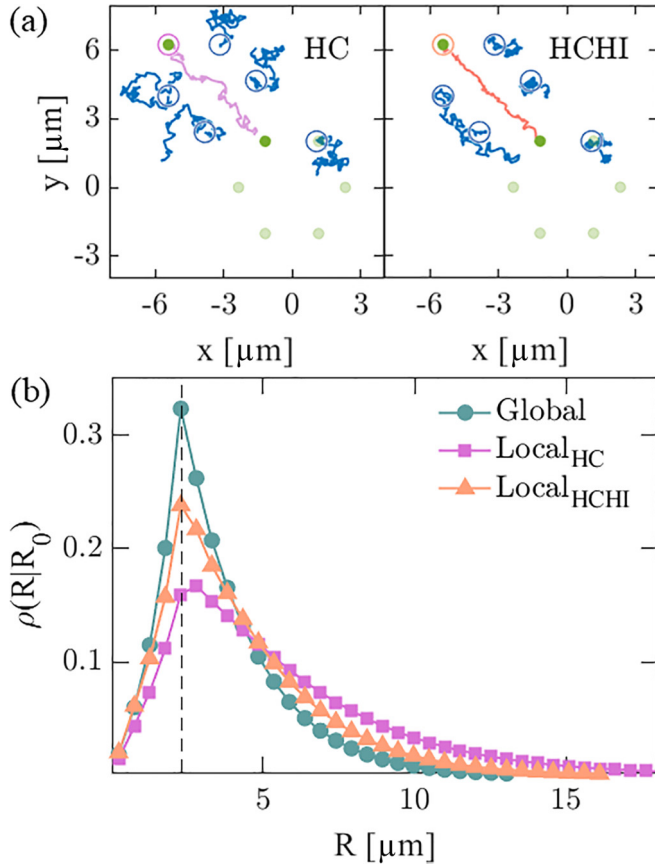


FIG. 5. Simulations comparing global and local returns. (a) Typical trajectories of the resetting particle (pink and orange) and the other five particles (blue) during a single reset event without (left panel, HC—hard core interactions only) and with hydrodynamic interactions (right panel, HCHI—also including hydrodynamic interactions). (b) Radial steady-state distribution from simulated data of different resetting protocols and particle interactions: global resetting with $r = 0.3$ with hydrodynamic interactions (blue circles) and local resetting with $r = 0.05$ without hydrodynamic interactions (pink squares) and with hydrodynamic interactions (orange triangles). All simulations involved a constant return time protocol (3 s). The black dashed line represents the initial and resetting position.

The simulation resetting protocols mirrored those of the experiments. A total of 10 000 return events had been recorded. Following our experimental design, we compare global and local protocols while maintaining a constant per-particle resetting rate, albeit with different free diffusing times per particle. Figures 5(a) and 5(b) illustrate simulated trajectories of a particle suspension where one particle is actively reset to the nearest trapping position, both with and without hydrodynamic interactions. Light green circles show the reset positions, the particle trajectories are traced in blue, and the particle undergoing resetting is highlighted in green, with its trajectory in pink (without hydrodynamic interactions) or orange (with hydrodynamic interactions). A striking difference emerges between the two scenarios: In the absence of hydrodynamic interactions, the resetting particle merely pushes away any particle it collides with, whereas in their presence the fluid flow created by its motion pulls nearby particles along in the same direction.

In Fig. 5(c), we plot the steady-state distribution in the radial direction along the line connecting the origin with each hexagon vertex, averaged over all six directions. Local resetting, both with (orange triangles) and without (pink squares) hydrodynamic interactions, yields a wider distribution than that of global resetting, reflecting the impact of collisions during return [as shown in Fig. 5(a)] that do not occur in global resetting. Notably, the resetting rate per particle is $r = 0.05 \text{ s}^{-1}$ in all simulations, meaning the total local resetting rate is effectively six times faster. Furthermore, in the absence of hydrodynamic interactions, the steady-state distribution broadens more, indicating that hydrodynamic interactions partially mitigate the collisional effect by narrowing the distribution.

An intuitive explanation for the observed narrowing effect stems from the distance dependence of hydrodynamic interactions, which decay as r^{-1} in an unbounded fluid [40]. The flow field generated by the dragged (resetting) particle entrains neighboring particles in a spatially dependent manner: Those closer to the source experience a stronger inward pull, while those farther away, on the opposite side of the hexagon, are subjected to a weaker outward push. This spatial asymmetry in the induced flows, when averaged over many return events, results in a net inward bias that progressively narrows the steady-state distribution.

In our experiments, however, the particles are suspended near a solid boundary, which significantly alters the nature of hydrodynamic interactions [34]. The presence of the wall modifies the mobility tensor, leading to faster decay (r^{-3} and r^{-5} for motion parallel and perpendicular to it). These steeper decays weaken the range and strength of the entrainment, thereby reducing the magnitude of the narrowing effect observed experimentally compared to simulations conducted in bulklike conditions.

Conclusions and discussion. In this Letter, we used holographic optical tweezers to implement different stochastic resetting protocols on a colloidal suspension. Our approach combines experiments with computer simulations to examine how interparticle interactions shape the emergent steady-state distribution. We observe that collisions and hydrodynamic effects play a key role, particularly during the resetting process, underscoring the importance of interactions in determining the steady-state distribution.

For global instantaneous resetting, where particles are returned to the origin simultaneously, the measured steady-state distribution can still be predicted from the many-body propagator using the renewal approach, as in single-particle resetting. In our implementation, we reset particles by optically trapping and translating them to the origin in a controlled manner. This procedure largely suppresses interactions during the return phase, allowing the system to remain accurately described by the renewal framework in combination with known particle trajectories. The resulting agreement between theory and experiments suggests that renewal approaches can be valid even in many-particle systems with collisions and hydrodynamic coupling.

By contrast, local resetting does not simply reset all particles at once; only a single particle is returned while others continue diffusing. This blends the return phase and the exploration phase, so the free propagator alone is no longer

sufficient to predict the steady-state distribution. In our experiments, we also observe unintended partial returns, where nontargeted particles are inadvertently dragged partway or even entirely back to the origin during a local resetting event. These additional interactions further affect the steady-state distribution, introducing a partial-resetting component not captured by the single-particle propagator. Overall, this interplay underscores the pronounced influence of many-body effects in shaping the final distribution when local resetting is used.

Overall, our results demonstrate that the resetting protocol, in terms of both sequence and timing, plays a pivotal role

in how interactions shape the steady-state distribution, particularly when the return and exploration phases are mixed. Moreover, different types of interactions can compete, either broadening or narrowing the distribution. Finally, given that stochastic resetting is increasingly employed to accelerate search processes, our findings offer valuable insights into designing many-body search strategies in the presence of interparticle interactions.

Data availability. The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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