Pedestrian bottleneck flow when keeping a prescribed physical distance

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(Received 2 May 2022; revised 19 September 2022; accepted 26 September 2022; published 10 October 2022)

We present experimental results of pedestrian evacuations through a narrow door under a prescribed safety distancing of either 1.5 or 2 meters. In this situation, flow rate augments with pedestrian velocity due to a complete absence of flow interruptions or clogs. Accordingly, the evacuation improves when the prescribed physical distance is reduced, as this implies shortening the time lapses between the exit of consecutive pedestrians. In addition, the analysis of pedestrian trajectories reveals that the distance to the first neighbor in the evacuation process is rather similar to the one obtained when pedestrians were just roaming within the arena, hence suggesting that this magnitude depends more on the crowd state (desired speed, prescribed safety distance, etc.) than on the geometry where the pedestrian flow takes place. Also, an important difference in pedestrian behavior is observed when people are asked to walk at different speeds: whereas slow pedestrians evidence a clear preference for stop-and-go motion, fast walkers display detouring and stop-and-go behavior roughly in the same proportion.

DOI: 10.1103/PhysRevE.106.044302

I. INTRODUCTION

The problem of room evacuation, or pedestrian bottleneck flow, is one of the most extensively studied in the field of pedestrian dynamics [1,2]. Apart from its crucial importance in real applications (prevention of congestion and fatalities, design of evacuation protocols, etc.) [3,4], this scenario has also aroused scientific interest for its connection with the bottleneck flow of systems such as colloidal suspensions [5], granular media [6,7], microbial populations [8], or active particles in general [6,9]. As a result, vast knowledge has been gained in the last couple of decades, yet several issues remain puzzling. For example, it is rather well accepted that flow decreases when the crowd competitiveness increases to very high levels, a behavior that is known as "faster is slower" [1]. Nevertheless, it is still not totally clear whether the origin of this flow reduction is simply associated with an increase of density at the bottleneck, or if it is necessary that contact forces among pedestrians build up to provoke transient clogs [9,10]. Also, the width of the evacuated room [11], the position of the door with respect to the walls [12], the effect of having multiple exits [13], or the role of an obstacle in front of the exit [14,15] are topics being actively investigated. Despite the advancements being significant, many questions are still open.

Besides, the COVID-19 pandemic importantly altered the way in which pedestrians behave, especially in closed areas. Obviously, this new scenario attracted the attention of researchers from different fields who are implementing investigations in three complementary ways: through real (empirical) measurements [16–19], by means of controlled experiments [20–23], and by developing numerical models [24–27]. Therefore, with people trying to keep a larger interpersonal distance in crowded environments, it is expected that bottleneck flow processes are affected, at least those in which competitiveness is limited because a real danger is not appreciated by pedestrians. Indeed, this is precisely what has been recently shown by Ronchi *et al.* [23], who evidence that imposing physical distancing implies lowest density levels, leading to lower flow values and higher evacuation times.

In this study, we experimentally investigate the problem of bottleneck flow for pedestrians keeping a prescribed physical distancing. We focus on the role of three variables: the prescribed safety distance (PSD), the crowd size, and the walking speed requested of the volunteers. The work is organized as follows: first we will describe the experimental protocol, then we will analyze several magnitudes related with the flow rate at the door, and finally we will present results of the pedestrian motion in their way out from the arena. At the end, the main conclusions will be summarized and contextualized with previous works of both bottleneck flow and pedestrian motion keeping a prescribed physical distance.

II. EXPERIMENTAL PROTOCOL

The evacuation drills were conducted as a continuation of the pedestrian roaming tests described in [20,21]. As explained there, all experiments were carried out in accordance with the guidelines and regulations applying on 23 June 2020 by the regional (Navarra) and national (Spain) Governments. In particular, all participants gave informed consent and wore a mask during the three hours they stayed in an indoor hall at the University of Navarra.

We recruited 38 volunteers (28 men and 10 women) aged between 19 and 59 years. From these, different subgroups of

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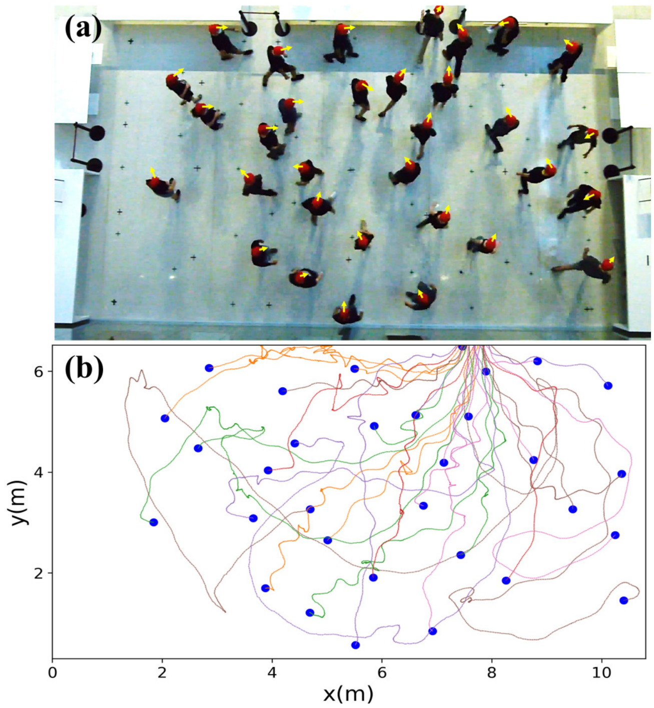

FIG. 1. (a) Snapshot of an evacuation of 32 pedestrians keeping a prescribed safety distance of 1.5 m after roaming the room at fast speed (see text for details). The yellow arrows indicate the motion direction of each pedestrian, showing how some of them move away from the door in order to be able to respect the requested physical distance. In (b) the corresponding positions of pedestrians are displayed with blue dots and their trajectories with lines of different colors.

12, 18, 24, or 32 participants were asked to walk within a rectangular enclosure (11.4 m wide by 6.7 m long as shown in Fig. 1) while keeping a prescribed safety distance (PSD = 2 or 1.5 m) at a given speed (either fast or slow). In order to check the reproducibility of the experiments, each condition was repeated twice with different people. In this way, a total of 24 runs were performed for 12 different experimental scenarios: 12, 18, 24 people for PSD = 2 m (fast and slow) and 18, 24, 32 people for PSD = 1.5 m (fast and slow).

For each run, the procedure was the following: first, pedestrians entered the enclosure and placed themselves at one of the marks drawn on the floor at a distance of 1.5 or 2 m from the others. These spots also served as a reference for participants to estimate the physical distance they had to keep. Then, volunteers were asked to roam within the enclosure keeping the prescribed distance and avoiding stopping as much as possible. In the case of slow walking, they were asked to roam peacefully, as if they were window-shopping in the street with no rush at all. In the case of fast walking, they were just requested to walk fast, without giving further details. After about 120 s since the start of the run, volunteers were asked to evacuate the enclosure through one of the 90 cm wide exits, arbitrarily chosen among the four that can be identified in Fig. 1. Note that the exit door was different at each run and this was not known in advance by the participants to avoid them concentrating in the exit proximities before the evacuation took place. As the roaming motion was already described in previous works [20,21], here we will only focus on the evacuation procedures under prescribed safety distance. Incidentally, note that the door size is below the prescribed distances investigated, so only one pedestrian can cross the exit at a time. Therefore, we do not expect a noteworthy influence of the exit size provided that it is kept well below the interpersonal distance established among participants.

All experiments were recorded with a 4K resolution camera at a frame rate of 25 fps, which allowed us to track the positions of all pedestrians and obtain several derived magnitudes such as flow rate, headway time (time lapse among two consecutive pedestrians passing through the exit), and distance to the nearest neighbor.

III. RESULTS

A. Flow rate

First, in Fig. 2(a) we show the number of evacuated pedestrians versus time for six representative experimental conditions. All of them correspond to a prescribed physical distance of 1.5 m, while the walking speed and total number of pedestrians within the room (crowd size, denoted by N) vary. Clearly, there is a significant effect of the walking speed (fast pedestrians evacuate more efficiently as revealed by the higher slope of the curves), whereas the crowd size seems to have a negligible effect (the three curves fall more or less on top of each other). These two results are both in agreement with a scenario of physical distancing (absence of physical contacts) in which the flow rate is determined locally (at the door) and conflicts are solved almost instantaneously. The same reasoning would justify the absence of a transient in the flow rate that is typically found in competitive evacuations or in those scenarios where a "social pressure" may drive first pedestrians to evacuate faster [28,29].

Next, we compute the average flow rate for each one of the 24 evacuation drills, and represent the data in Fig. 2(b). There, it is confirmed that the established flow rate increases with requested pedestrian velocity while it remains independent of the total number of people in the room. Furthermore, we observe a weak but consistent dependence on the prescribed safety distance: the higher PSD is, the lower the flow rate. This result could be expected, as the distance among pedestrians near the door will increase with a larger PSD, and so does the time elapsed between the exit of two consecutive pedestrians. As a result, the flow rate is reduced.

Aiming to support this hypothesis, we computed the headway times, τ, defined as the time gaps in the passage through the exit among consecutive pedestrians. In Fig. 3 we display different plots with the resulting statistics after grouping all tests performed with a different number of pedestrians but otherwise identical experimental conditions (i.e., walking speed and PSD). The box plot [Fig. 3(a)] corroborates our expectations, as for a given value of the walking speed the values of τ for PSD = 2 m are, on average, above those for PSD = 1.5 m. The dependence seems to be more noticeable when people walk slowly, a behavior that can be understood if τ is just assumed to be related with a characteristic distance (that will increase with PSD) multiplied by the characteristic walking velocity. Another interesting feature that is evidenced

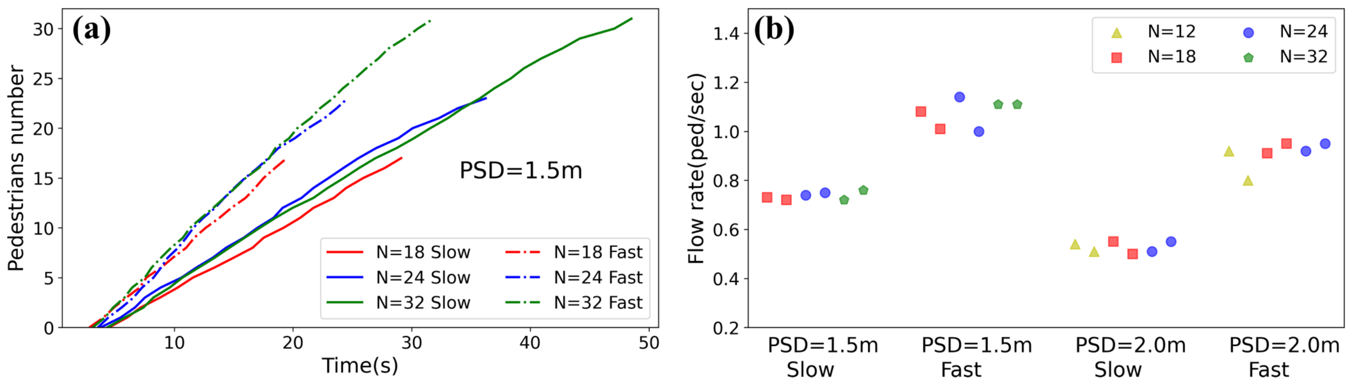

FIG. 2. Flow rate through the door. a() Number of pedestrians that exit the enclosure versus time for a prescribed physical distance of 1.5 meters. Different colors and line styles correspond to different initial numbers of pedestrians within the room (N) and walking speeds (S, slow; F, fast) as shown in the legend. (b) The average flow rate obtained for the 24 drills implemented. Different symbols are used for experiments with different number of pedestrians (see legend).

in Fig. 3(a) is that data for slow walking speeds are more dispersed than for high walking speeds. This is confirmed by the representation of the probability density functions PDF(τ) in Fig. 3(b). Clearly, the expected shift of the peak value towards higher values of τ, when either PSD increases or walking speed decreases, is coupled with an important widening of the distributions. In order to explain this, one may argue that the distribution of distances among pedestrians also widens when increasing PSD [20]. Anyway, the distributions seem to be rather symmetric and no sign of fat tails (as the ones observed in competitive evacuations [29]) is observed. Indeed, the absence of these fat tails is shown in Fig. 3(c), where the survival functions of τ reveal a decay compatible with an exponential tail (note the semilogarithmic scale of the plot). The absence of fat tails indicates that flow interruptions or clogs are not developed during the evacuations.

B. Pedestrian motion within the crowd

Once we have analyzed in detail the flow rate properties of the crowd in different experimental situations, we focus on the pedestrian motion in their way out. First, we analyze the interpersonal distance by representing in Fig. 4 the distributions of the distances to the closest neighbor of each volunteer PDF(d_1) during the whole evacuation process (i.e., since they are asked to evacuate until they cross the exit). In practice, the distances to the closest neighbours are computed every 1/25 seconds for all pedestrians remaining in the room. For comparison, we also represent the distributions obtained during the roaming (random) motion of pedestrians before the evacuation (already reported in [20]). As these PDFs displayed a clear dependence on the number of pedestrians within the room, we also make this distinction here. One could naively expect that people would get closer on their way out of the room than in the random motion within the arena, but the distributions show that the PDFs in the evacuations are similar (or slightly shifted towards higher values of d_1) than in the random motion. This suggests that the distance to the first neighbor is a magnitude intrinsic to the crowd state (size, desired speed, etc.) with a negligible dependence on the task that pedestrians are performing. Indeed, we speculate that the weak shift of the evacuation PDFs towards higher values of d_1 may be due to the fact that, as pedestrians leave the room, more space is available and the separation adopted by pedestrians can marginally enlarge. In addition, as already reported in [20], the trials in which PSD = 2.0 m evidence

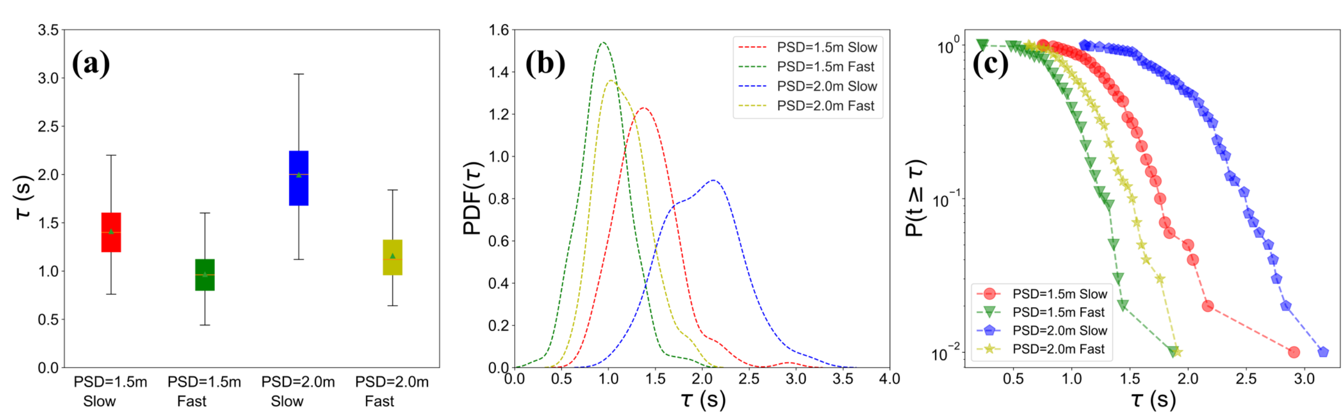

FIG. 3. Headway times. (a) Box plot of the headway times (τ) obtained for each experimental condition irrespective of the number of pedestrians; i.e., results with different number of people N are grouped provided that the prescribed physical distance and the walking speeds are the same. (b) Probability density function and (c) survival function (or complementary cumulative distribution) of the same data in semilogarithmic scale. In the three panels, the same colors are used for identical experimental conditions, as indicated in the legends.

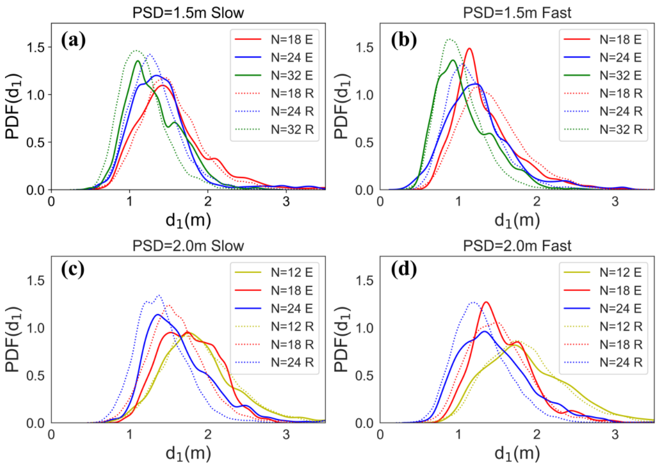

FIG. 4. Probability density functions of the distances to the nearest neighbor during the evacuation process. Plots (a)–(d) correspond to different prescribed safety distances and walking speeds as indicated at the top of each panel. Solid lines are used to represent the PDF(d_1) during the evacuation process and dashed lines to illustrate already known distributions during the roaming (random) motion. Distinct colors are used depending on the number of pedestrians within the enclosure (see legends, where E corresponds to evacuations and R to roaming motion).

wider distributions than those in which PSD = 1.5 m, hence supporting the hypothesis of this variable being behind the augment of τ with PSD discussed in the previous section.

Next, to better characterize pedestrian motion, we build a plot in which we represent the time to target (exit door) versus the distance to it for each individual [see examples of these plots for two experimental conditions in Figs. 5(a) and 5(b)]. Obviously, all lines in the plot end up at (0,0). Remarkably, for the two examples reported in Figs. 5(a) and 5(b), we observe a number of pedestrians starting their motion by walking away from the door (i.e., the distance to the target increases). This detouring behavior is something generally occurring, in a greater or lesser extent, in all the scenarios investigated. Another characteristic behavior that can be identified, especially when pedestrians walk slowly as in Fig. 5(a), is stop-and-go motion. In the plots, stopping events lead to the appearance of vertical lines (the distance to the target keeps constant while the time reduces). The colors of the lines (encoding the actual speed of pedestrians obtained from their real positions) help one visualize this characteristic stop-and-go behavior.

Aiming for a quantification of the disposition of pedestrians to behave in one way or another (stop-and-go or detouring), and the possible behavioral dependence on the walking velocity and size of the crowd, we have classified each individual according to their evacuation strategy (characterized by both the trajectory and velocity). First, pedestrians will be assigned to behave in a detouring manner if the total length of their trajectories is longer than 1.5 times their initial distance to the exit. On the other hand, pedestrians will be classified within a stop-and-go behavior if they stop at any time during the evacuation. In practical terms, we consider that a pedestrian has stopped whenever a speed lower than 0.05 m/s is attained. In Figs. 6(a) and 6(b) we display the trajectories of pedestrians for the same experimental conditions represented in Figs. 5(a) and 5(b) with colors encoding the group within which each pedestrian is classified. Note that a pedestrian may not belong to any group or may belong to both groups provided that he/she fulfills the two conditions.

After this classification is applied, in Fig. 6(c) we report the proportion of pedestrians falling in each group (note that the total does not add to 1 as some pedestrians may belong to both groups or none). The first salient result is that, given a number of pedestrians, an increase of walking speed implies a reduction of the stop-and-go behavior and an augment of

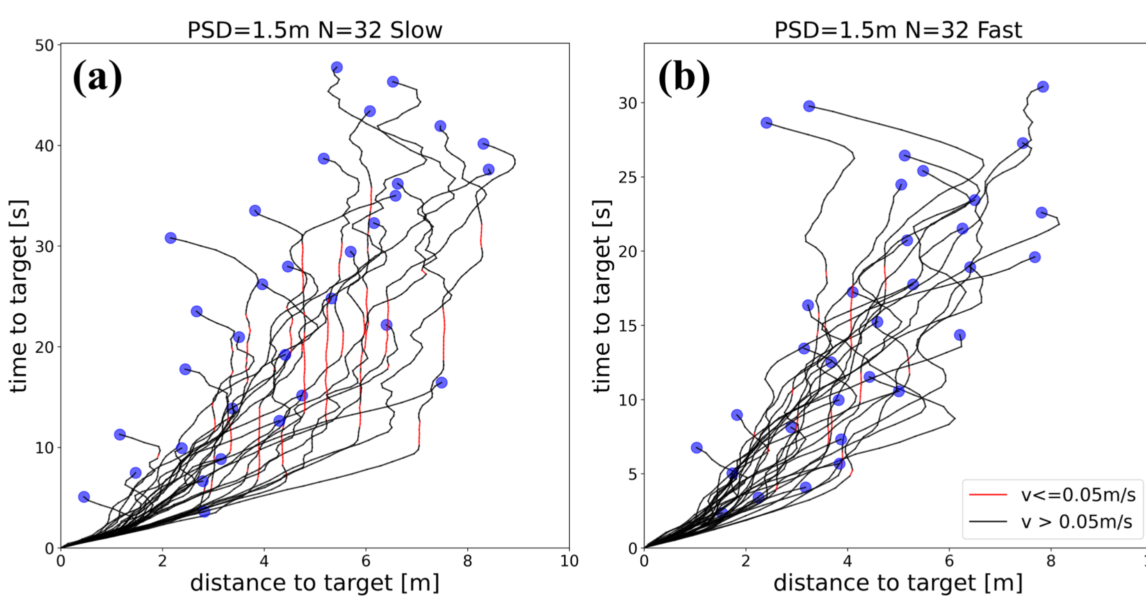

FIG. 5. (a),(b) Time to target vs distance to target plots of two representative scenarios as indicated at the top of each panel. Blue dots correspond to the initial positions and times; the lines illustrate the trajectories of each individual with color encoding the speed value as indicated in the legend.

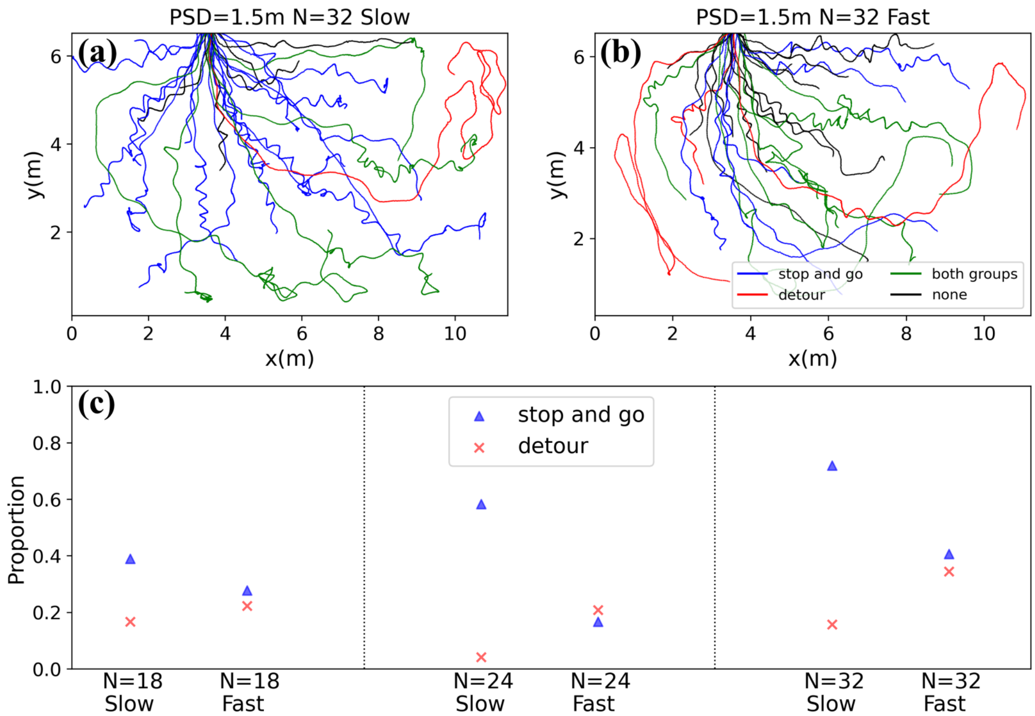

FIG. 6. (a),(b) Trajectories corresponding to the same scenarios reported in Figs. 5(a) and 5(b). Colours (see legend) indicate the behavior of each individual as explained in the main text. (c) Proportion of pedestrians following a detouring and a stop-and-go behavior (see text for definition) for PSD = 1.5 m and different crowd sizes and walking speeds as indicated in the x axis of the plot.

detouring motion. This can be understood as a result of behavioral inertia: pedestrians walking fast within the enclosure for about two minutes (in the random motion) are less prone to stop (and wait) during evacuation than those that have been walking slowly. In addition, we observe that the size of the crowd does not appreciably affect the proportion of people displaying detouring, but it does affect the proportion of individuals showing stop-and-go behavior when the walking speed is slow. Indeed, the proportion almost doubles (from around 0.4 to 0.75) when increasing the crowd size from 18 to 32 individuals. In contrast, when the walking speed is fast, the proportion of stop-and-go motions stays more or less constant within a range of 0.2–0.4.

IV. CONCLUSIONS

In this work we have reported new experimental results on pedestrian bottleneck flow in a scenario of prescribed physical distancing. In these special conditions, flow interruptions are completely absent and the flow rate (and thus the evacuation efficiency) increases by augmenting the walking speed and reducing the physical distancing. Also, we observe that the flow rate is independent of the crowd size, a feature that suggests absence of psychological crowd pressure, or at least a negligible effect of it on the evacuation process. On the other hand, the analysis of pedestrian motion when approaching the exit reveals a remarkable role of the crowd size on the emerging collective dynamics. In this way, the proportion of pedestrians performing a stop-and-go motion notably enlarges when increasing the crowd size, provided that the walking speed is slow. This dependency is not observed for the proportion of people displaying detouring behavior, which increases with the walking speed but stays independent of the crowd size.

The apparent dichotomy concerning the role of the crowd size (it has no effect on the flow rate, but it clearly determines the dynamics of pedestrians on their way out) can be disentangled if we understand that, in the special conditions of physical distancing in which the evacuations were performed, the flow rate is only locally regulated at the very exit. There, the outflow is inversely proportional to the time it takes since a pedestrian leaves the door until another one is able to reach it, a magnitude that, in the diluted conditions created when imposing physical distancing, is solely determined by the pedestrian walking speed and the interpersonal distance at the exit. Therefore, one can understand the positive effect on the flow rate of increasing the walking speed and reducing the prescribed safety distance, as well as the negligible effect of pedestrian motion far from the exit, and thus the size of the evacuated crowd. A confirmation of this hypothesis is made by looking at the speeds of pedestrians when they approach the exit (computed during the last second within the arena) as shown in Fig. 7. Clearly, there is not a measurable effect of the size of the crowd on pedestrians' speeds at the door, which are mainly affected by the requested walking velocity. Also, for slow pedestrians the prescribed safety distance does not affect the pedestrians' speeds, whereas for fast pedestrians higher speeds are achieved when the prescribed safety distance is larger. The latter could be explained by considering that pedestrians accelerate at the bottleneck (departing from very low velocities), a process that would be better accomplished when the distance to the preceding individual is larger. Moreover, This phenomenon could be related to the smaller difference among the flow rates measured for fast

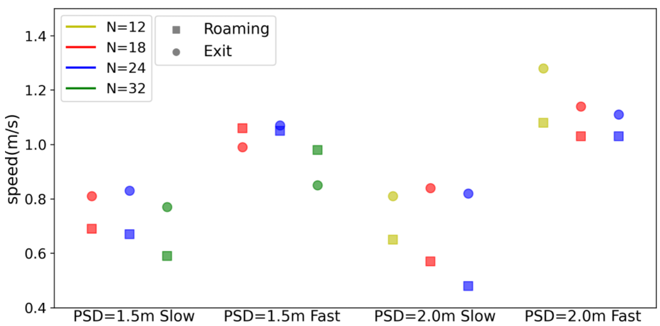

FIG. 7. Average pedestrian speed during the last walking second before crossing the exit (circles) compared with the average speed during roaming within the enclosure (squares). Results are presented for the diverse experimental conditions explored in this work as indicated by the legend and in the x axis of the plot.

pedestrians (and different prescribed safety distances) than for slow pedestrians. Finally, let us note the correlation among the pedestrian speeds at the exit and the ones during roaming. Although the former are systematically higher, the dependences on the prescribed safety distance and the requested walking speed follow the same trends.

An important question for the field of pedestrian dynamics that remains unsolved concerns the possible existence of an optimal prescribed safety distance that maximizes the exit flow. Provided that the occurrence of the faster-is-slower effect has been demonstrated to be in close connection with the appearance of clogs [9], the minimum prescribed safety distance at which clogs are not present can be speculated to be a good recommendation for optimizing the outflow. Although this quantification is out of the scope of this work, we believe it is an interesting followup project that could be approached numerically.

ACKNOWLEDGMENTS

This work was possible thanks to the Grant PID2020-114839GB-I00 funded by MCIN/AEI/10.13039/501100011033. I.E. acknowledges Asociación de Amigos de la Universidad de Navarra for his grant. Z.S. acknowledges China Scholarship Council (CSC) for a traveling grant.

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