Properties of pedestrians walking in line. II. Stepping behavior

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In human crowds, interactions among individuals give rise to a variety of self-organized collective motions that help the group to effectively solve the problem of coordination. However, it is still not known exactly how humans adjust their behavior locally, nor what are the direct consequences on the emergent organization. One of the underlying mechanisms of adjusting individual motions is the stepping dynamics. In this paper, we present first quantitative analysis on the stepping behavior in a one-dimensional pedestrian flow studied under controlled laboratory conditions. We find that the step length is proportional to the velocity of the pedestrian, and is directly related to the space available in front of him, while the variations of the step duration are much smaller. This is in contrast with locomotion studies performed on isolated pedestrians and shows that the local density has a direct influence on the stepping characteristics. Furthermore, we study the phenomena of synchronization—walking in lock step—and show its dependence on flow densities. We show that the synchronization of steps is particularly important at high densities, which has direct impact on the studies of optimizing pedestrians' flow in congested situations. However, small synchronization and antisynchronization effects are found also at very low densities, for which no steric constraints exist between successive pedestrians, showing the natural tendency to synchronize according to perceived visual signals.

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I. INTRODUCTION

As in many biological systems, such as fish schools, flocks of birds, or ant colonies, the dynamics of large pedestrian groups are governed by local interactions between individuals which give rise to a variety of collective motions occurring on a macroscopic scale [1,2]. Such self-organized behaviors of large pedestrian groups are studied for practical and safety reasons—improving pedestrians facilities and preventing accidents in emergency regimes—but also as an intriguing problem of out-of-equilibrium physics.

When pedestrians are separated by a small distance, they cannot walk freely. It is an open question how they adapt to large densities. Indeed, it is known that large density pedestrian flows give rise to increasing fluctuations in the individual motions, that can eventually lead to the so-called "crowd turbulence" [3] known to be responsible for crowd disasters. A careful analysis of the behavior of pedestrians at relatively high densities can give information on the individual behaviors that could lead to such transitions.

When pedestrians are very close to each other, the distance between them can become of the same order as the longitudinal displacement due to steps. Besides, accelerations and decelerations occur on time scales similar to the stepping period. Thus steps cannot be ignored when dealing with high density flows. In fact, it was observed in the videos of the experiments reported in Ref. [4] that, at high densities, people were walking in lock step (which we term here also "synchronization" of steps) in order to optimize the use of the available space.

Interactions between pedestrians usually take place in a two-dimensional space and produce velocity changes in direction and modulus. However, there are situations where interactions are mostly longitudinal, for example, when people are walking along a narrow corridor. It is also known that counterflows—pedestrian flows of opposite direction—induce lane formation [5,6], and within these lanes longitudinal interactions should dominate. Indeed, some previous experiments have suggested that the adaptations of velocity in angle and in modulus could be decoupled to some extent [7]. This decoupling has already been used in some models [7,8].

As one-dimensional pedestrian flows involve purely longitudinal interactions which induce only changes in the velocity modulus,[1] a lot of interest has been shown recently in studying how pedestrians follow each other in such settings. From the point of view of modeling, one-dimensional flows can serve as a simple test of a model's ability to produce following behavior. The experiment is easier to interpret if periodic boundary conditions are used, i.e., pedestrians walk on a closed line. Indeed, the transients that may occur when pedestrians enter or exit an experimental setup are then avoided. Besides, the global density is constant in a closed system, while it is more difficult to control it in an open system. Such experiments have been already conducted in recent years. Seyfried *et al.* [4,9,10] have performed experiments with pedestrians following an

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[1]Of course, a one-dimensional path may not be straight and pedestrians may have to change their velocity orientation to follow the path. However, if direction changes are not too abrupt, they should have no influence on the velocity modulus.

oval path. Similar studies have been reported in Refs. [11,12]. These experiments have been performed either by using video analysis of the individual trajectories along one straight portion of the setup [10], or by measuring times at which each participant passes a given measuring point [12].

We have reported in Ref. [13] experiments where pedestrians were asked to follow circular paths. Pedestrians were tracked with a high precision motion capture device. As a result of being able to cover a larger range of densities than in previous experiments, we found that the behavior of a pedestrian following another one was exhibiting two transitions, when the distance between the pedestrians was becoming respectively less than 1.1 and 3 m [13,14]. Beyond this first result, as our experiments provide high precision tracking of all the individual trajectories during the whole duration of the experiment, we could access other features, either at more macroscopic scales (e.g., forming of jams) or microscopic scales (e.g., stepping dynamics), which were not accessible in previous experiments.

In this paper, we focus on the stepping dynamics in the one-dimensional pedestrian flow experiment presented in Ref. [13]. We perform the first quantitative analysis of the stepping dynamics in large pedestrians groups. We show that the size of steps is directly related to the space available in front of the pedestrian, and that the step frequency is far less sensitive to the local density. Furthermore, we examine the effect of the flow densities on the synchronization of steps among the consecutive pairs of pedestrians. We find as expected that a certain amount of synchronization occurs at high densities. However, more surprinsingly, we also find some synchronization at lower densities. Besides, at lower densities we also found occurrence of an "antisynchronization" phenomenon, i.e., a consecutive pair of pedestrians can be synchronized in such a way that when one of them is stepping with the left leg, the other is stepping with the right leg, and vice versa. This natural tendency to synchronize could actually be exploited to improve the flow in a congested situation, for example using the effect of rhythm and music on the stepping behavior [12,15].

First we shall summarize the experimental protocol (Sec. II). Step measurements are described in Sec. III. In Sec. IV we present results showing that step length and duration obey simple laws. Section V is devoted to the study of step synchronization.

II. EXPERIMENT

The aim of the experiment was to study the longitudinal interactions between pedestrians walking in line, without overpassing each other, along a circular path. While the study of the fundamental diagrams and velocity-spatial headway relation was presented in Ref. [13], here we focus on the extraction of the stepping behavior in the various dynamic regimes (free flow, jammed, etc.).

As detailed in Ref. [13], the experiment was performed inside a ring corridor formed by inner and outer circular walls of radii 2 and 4.5 m, respectively (see Fig. 1). Participants were told to walk in line along either the inner or outer wall, without passing each other. As a result, we obtained two types of pedestrians trajectories: along the inner circular path the observed average radius of the trajectories was 2.4 m, and along the outer circular path, the observed radius was 4.1 m.

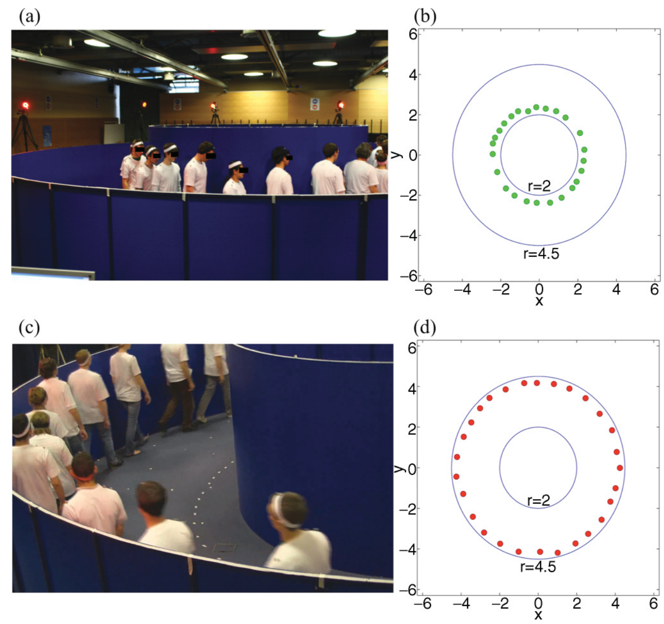

FIG. 1. (Color online) Experimental setup: (a) and (c) photo of the experiment and (b) and (d) top view obtained through MATLAB treatment of the data, showing a snapshot of the pedestrians positions (small circles). The experimental setup is made of two cylindrical walls surrounded by infrared cameras. In the experiment, pedestrians were asked to walk either along the inner wall (top images) or along the outer wall (bottom images). The top figures are taken from Ref. [13], which describes another aspect of the same experiment.

Pedestrians were volunteers, unaware of the goal of the experiment. In order to capture their most natural (real situation) behavior, even though in laboratory conditions, they were asked to walk in a "natural way," as if they were walking alone in the street (and without talking to each other). Up to 28 pedestrians (20 males and 8 females) were involved in the experiment. The average global density was varied from 0.31 to 1.86 ped/m[2] by varying both the number of participants involved and the length of the circular trajectory.

Each participant was equipped with four markers (one on the left shoulder, two on the right shoulder, and one on top of the head). Motion was tracked by 12 infrared cameras (VICON MX-40 motion capture system). The raw data were turned into three-dimensional marker trajectories using the reconstruction software VICON IQ, with a frequency of 120 frames per s (for more details, see [16]).

[2]For bidimensional pedestrian crowds, densities are expressed in ped/m^2. An attempt to make a connection between one- and bidimensional densities was proposed in Ref. [4]. It is based on the assumption that the lateral width required by the one-dimensional flow increases with the velocity. If we use a transformation such as suggested in Ref. [4], namely $\rho_{1D\to 2D} = \rho_{1D}/(0.46 + 0.2v)$, then the estimate for the density range covered by our experiment would extend from 0.4 to 3.7 ped/m^2 (using the velocity-density relation measured in Ref. [13]). But of course these figures should be taken only as a rough estimate.

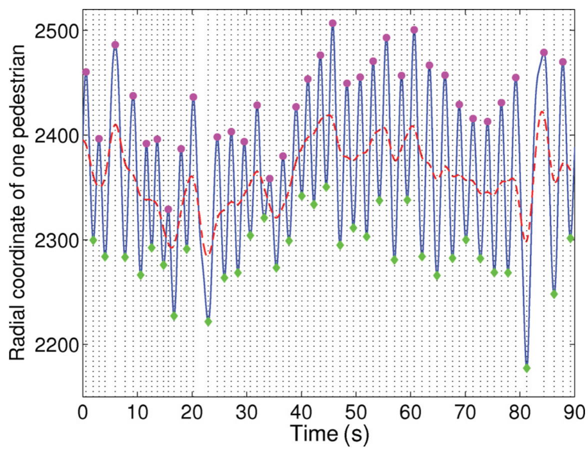

FIG. 2. (Color online) Full (blue) line is the nonfiltered radial coordinate of one participant (in mm), walking along the inner circle trajectory of average radius 2.4 m, with clearly visible oscillations due to the consecutive steps. The dashed (red) line is the filtered radial coordinate (we used a second-order low pass butterworth filter). Thin vertical lines (· · ·) mark the local extrema—local maxima (magenta circles) and minima (green diamonds)—which are used in our definitions of step characteristics.

The trajectories of the markers belonging to the same pedestrian were aggregated[3] in order to give one single three-dimensional trajectory for each pedestrian: its radial, angular, and height coordinates are given as a function of time during the whole duration of experiment. The corresponding velocities are easily calculated.

III. STEP MEASUREMENTS

In our previous paper on these experimental data [13], we were interested in properties like fundamental diagrams and velocity-spatial headway relations, and therefore we used filtering in order to eliminate the oscillations of the trajectories due to stepping. Here, on the contrary, we focus on these oscillations.

The whole body of a pedestrian is swaying when the body weight is shifted from one leg to the other. This swaying results in oscillations that can be seen on the three coordinates of a given pedestrian. However, the angular coordinate oscillations are entangled with the average forward motion of pedestrians, and the height data can be spoiled with spurious motion of the pedestrian head. Therefore, we found that the radial coordinate is the one yielding the best signal for the detection of the stepping cycles (see Fig. 2). Indeed, stepping induces some lateral body movement clearly visible on the radial coordinate. Besides, as pedestrians are walking along circular paths, the radial coordinate is decoupled from the forward motion.

The high precision of our experimental measurements allowed us to extract information on the step length, step duration, and also to analyze the synchronization phenomena between two successive pedestrians.

We define step duration as the time Δt_s passed between two consecutive local extrema in the radial coordinate (consecutive local minimum and maximum of oscillations). The step length is then the distance that a participant has traveled along the circle during this time. It is defined as $l_s = \Delta\theta_s \langle R \rangle_s$, where $\Delta\theta_s$ is the angle covered during time Δt_s, and $\langle R \rangle_s$ the average of the radius of a circular trajectory along which a pedestrian is walking during step duration Δt_s.

One may argue that, as we do not track directly the foot motion, the oscillations that we detect on the radial coordinate could not rigorously coincide with the feet cycles. However, on average the step length and step duration values should be the same.

We performed analysis on the set of all steps made by each participant during all of our 52 experiments, each lasting about 1 min. On average, step duration is estimated to be of the order of 1 s, meaning each participant made approximately 60 steps during one experiment. We kept only data with at least two visible markers at each time frame between two steps (two local extrema), the rejection ratio being around 10%.

IV. STEPPING LAWS

In Fig. 3 we show the results for the relationship between the step length (respectively step duration) and the instantaneous velocity (top) and density (bottom). The values of velocity and density were obtained as averages of the instantaneous velocity and density during the duration of a given step. For two successive pedestrians, instantaneous density for the pedestrian in the back is obtained as the inverse of the distance that is available in front of him, i.e., to his predecessor.

The most striking feature is that the step length is overall proportional to the velocity, up to velocities very close to zero [see Fig. 3(a)]. Of course, the step length decreases when the velocity decreases. Having a vanishing step length for vanishing velocities means that, within a jammed regime, when pedestrians are forced to come almost to a stop, they continue to sway and shift their body weight from one leg to the other

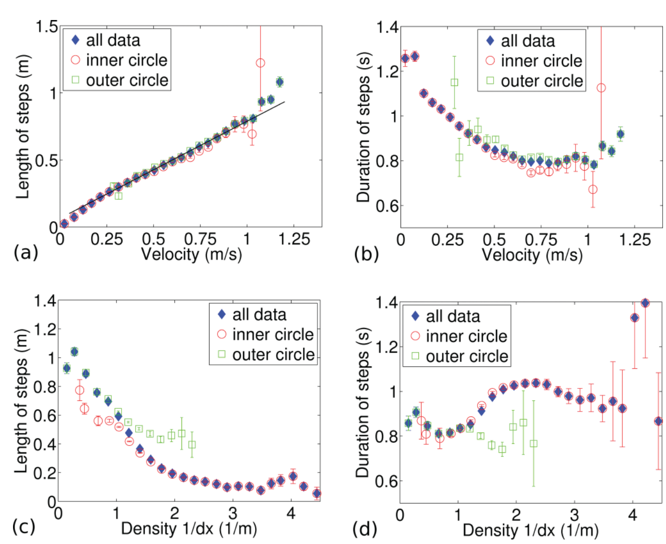

FIG. 3. (Color online) Dependence of the step length (left) and duration (right) as a function of the instantaneous velocity (top) and density (bottom).

[3]Some special care was necessary at this stage, since markers may be temporarily hidden by the walls or participants' bodies. We kept only data for which at least two markers per pedestrian were visible.

without moving forward. A linear fit for velocities between 0.2 and 1.1 m/s gives

$$l_s = 0.065 \text{ m} + 0.724v. \quad (1)$$

This differs from the expression given in Ref. [17] and used in Ref. [18] ($l_s = 0.235$ m $+ 0.302v$) for which a residual length of 0.235 m was found at vanishing velocity. However, the details of the measurements were not given in these references.

As the velocity of a pedestrian is mechanically produced by the steps, we have that $v = l_s/\Delta t_s$. As a first approximation, one can state from Fig. 3(a) that the velocity is proportional to the step length, and, as a consequence, the step duration should be constant. This is indeed what we find in Fig. 3(b) when the velocity is large enough (larger than 0.6 m/s): the step duration is then mostly constant and takes a value around 0.8 s. Even for velocities below 0.6 m/s, the variations in the step duration are only of 30%, to be compared with the 100% variation in the velocity. In a more accurate description, this increase of the step duration when the velocity of the participants decreases should be taken into account, yielding a more complex relationship between velocity and step duration.

At first sight, our results could seem in contradiction with those obtained in the field of locomotion studies: Inman's law [19] states that the step length [20,21] or step frequency [22] both vary as the square root of the velocity. This law has been indeed verified in locomotion experiments [22,23]. Note that Inman's law requires one to normalize data either by the hip joint height, or total height of the pedestrian—information that is not available in our case, but that could be measured in future experiments. However, this renormalization cannot explain the difference with our result.

In fact, it must be noted that locomotion experiments are always performed with *isolated* pedestrians. The pedestrian makes a conscious decision to walk slowly, and knows that he will keep this slow pace for a while. In our experiment, participants walk slowly only because they are prevented to walk faster by other participants. Besides, they expect to be able to walk faster in the near future. As a consequence of these features, our pedestrians keep a constant pace (to enable a quick restart), and rather adopt small step lengths (to comply with steric constraints).

We have observed that pedestrians continue to take step even for vanishing velocities. In order to interpret this result, it should be underlined that the vanishing velocities measured in Fig. 3(a) are transients: pedestrians perform one or two steps with vanishing amplitude and then start again moving forward. In the case where pedestrians would be standing for a longer time, one could expect pedestrians to be more reluctant to use their energy in swaying when they cannot move forward. It is also the transient nature of the flow that could explain that the step duration is bounded within a 30% variation: pedestrians probably do not like rapid modifications of their stepping pace.

As a conclusion, we observe that in a constrained environment, pedestrians rather adapt their velocity through their step length rather than step frequency. Note that, in Figs. 3(a) and 3(b), the data obtained both along the inner and outer circle fall on top of each other. This seems to indicate that there is little influence of geometry on the stepping behavior.

Let us now consider the dependence of the steps characteristics with the density. The behavior of the step length as a function of density [see Fig. 3(c)] is exactly of the same form as the fundamental diagram found in Ref. [13]. Indeed, this is a direct consequence of the above result that the step length is being proportional to velocity. As the average velocity converges towards a finite nonzero value when the density becomes large, the average step length saturates around 0.1 m at large densities. By contrast, the step duration changes much less within different walking regimes. The step duration varies only for around 20% as a function of density [see Fig. 3(d)]. The saturation of step frequency at low densities (or high velocities) could indicate that increasing the step frequency beyond a certain value is not comfortable for pedestrians.

We had previously found in Ref. [13] that for local density fluctuations far away from the average global density the velocity could be quite different from the average behavior. We recover here [Figs. 3(c) and 3(d)] these atypical behaviors. Indeed, global densities in experiments performed on the outer (inner) circle are always below (above) 1 ped/m, and thus the tails ("inner and outer circle data") diverging from the average behavior ("all data") in Figs. 3(c) and 3(d) correspond to large fluctuations. Still, for the mean behavior, no discontinuity is seen when going from the inner to the outer circle data.

V. STEP SYNCHRONIZATION

It was already noticed in Ref. [4] that, at high densities, as pedestrians do not have much space to walk, they tend to synchronize their steps, so as to squeeze the front leg into the hole left by the front leg of the predecessor. The authors refer to this phenomenon as walking in lock step. In the following, we want to see whether this tendency is confirmed in our experiments, and to quantify this effect.

First we have to define synchronization. Full synchronization is obtained when two successive pedestrians walk with the same step frequency and in phase.

If all pedestrians were walking very regularly, so that their radial coordinate would be a perfectly periodic signal with the same frequency for all pedestrians, it would be quite easy to measure the phase between two successive pedestrians. However, in the experiments, and especially at high densities, the shape of the oscillations and the oscillation frequencies can vary from one pedestrian to another, and for the same pedestrian from time to time.

Thus our measurements included two stages that we will detail below. In a first stage, we have analyzed the data to select pairs of successive pedestrians for which the stepping frequencies were not too different. Then, for this subset, we have measured the phase shift between close minima (maxima) of the stepping cycles of the two successive pedestrians. More precisely, for each detected minimum (maximum) on the radial coordinate of the predecessor (occurring at time t_0) our analysis consists of the following steps.

(i) We measure the "individual and local" frequency of the leader over three periods, defined from the two maxima (minima) just before and after the given minimum (maximum). Let T be the average period over these three cycles.

(ii) We determine whether there is a minimum (maximum) in the radial coordinate of the follower within the time range $[t_0 - T/4, t_0 + 3T/4]$. This minimum occurs at time t_1.

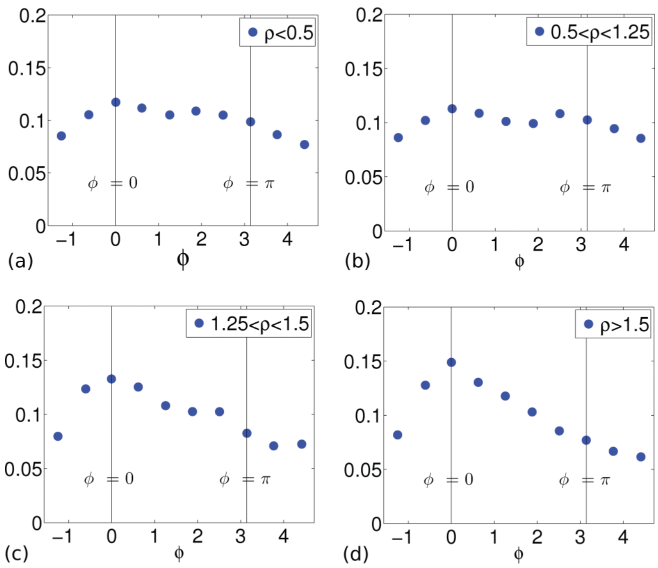

FIG. 4. (Color online) Normalized distributions of ϕ, for various density ranges. Synchronization corresponds to $\phi = 0$.

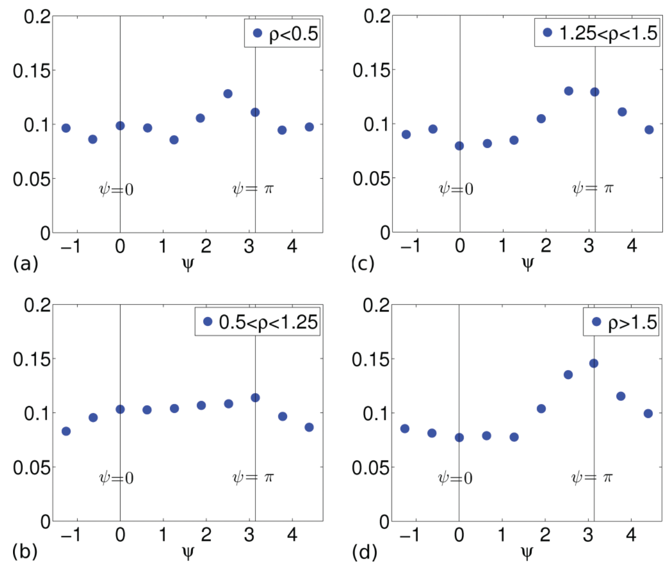

FIG. 5. (Color online) Normalized distributions of ψ, for various density ranges. Antisynchronization corresponds to $\psi = 0$.

(iii) We evaluate the "individual and local" frequency $1/T'$ for the follower, exactly as it was done for the leader.

(iv) If T' and T differ less than 25%, we select the current steps of this pair of pedestrians. The rejection ratio due to too large difference in frequencies is up to 20%. This underlines that at least 20% of the pedestrians are not synchronized with their leader, as synchronization requires first to have the same frequency.

(v) Then we measure the phase

$$\phi = 2\pi(t_1 - t_0)/T. \quad (2)$$

In a similar way, we also measure the phase ψ separating a minimum (maximum) in the radial coordinate of the leader, from a maximum (minimum) in the radial coordinate of the follower. In this way, we expect to obtain more precise measurements for the antisynchronization phenomena.

(vi) Finally, we measure the instantaneous density. It is defined as the inverse of the distance between the centers of mass of the two pedestrians. As this distance oscillates with the steps, we found more relevant to evaluate it on the filtered data. However, the results presented in Fig. 4 are similar when nonfiltered data are used.

Figure 4 shows the normalized histograms of ϕ obtained for various local density ranges. At large densities (beyond 1.25 ped/m), we observe a peak around phase $\phi = 0$, that clearly indicates existence of the synchronization phenomenon. This must correspond to the pedestrians walking in lock step; as for these densities the steric constraints become important.

When the density is lower, the peak around zero is still observed, though it is smaller than for higher densities. Surprisingly, another peak appears around $\phi = \pi$. This second peak corresponds to antisynchronization, i.e., walking in phase with the opposite legs. When antisynchronization occurs at high densities, we could expect that pedestrians would be located at different distances from the wall, so that the left leg of one pedestrian is more or less aligned with the right leg of the other. However, we did not observe any visible effect of this type in the data. Besides, antisynchronization mostly disappears when the density is large, while it survives at densities as large as $\rho < 0.5$ ped/m, for which there are clearly no steric constraints between the pedestrians.

As the pedestrians may not have exactly the same frequency, in Fig. 5 we checked if the antisynchronization is also visible when we measure the phase shift ψ between the local extrema of the opposite kind (minimum and maximum) in the radial coordinate. This corresponds to the steps made by the left leg of one and the right leg of the other of the two consecutive pedestrians. In this case, antisynchronization should appear as a peak around zero—and there is indeed a second peak located around $\psi = 0$ for the lowest densities as seen in Fig. 5. On the other hand, synchronization can be seen again, but this time as a peak around $\psi = \pi$.

These results, showing both synchronization and antisynchronization at low enough densities where the pedestrians are not bound by the steric constraints, suggest that pedestrians are sensitive to the stepping oscillations that they perceive visually when watching their predecessor, and that they naturally synchronize. It is still an open question to determine precisely to which visual signal pedestrians are most sensitive. Rather than lateral or vertical oscillations of the body, pedestrians probably perceive more easily the motion of arms and legs [24].

VI. DISCUSSION AND CONCLUSION

In this paper, we have presented experimental results about steps characteristics of pedestrians following each other along a one-dimensional trajectory. We have obtained for a large range of velocities several simple laws for step length and duration, namely that step length is proportional to velocity, while variations in step duration are much smaller.

This result is in contrast with the hypothesis used in Ref. [25] that at high densities, when it is no longer possible to take normal steps, pedestrians would rather completely stop until they gain enough space to make a step. Indeed our observation is that pedestrians are not reluctant to take very short steps and continue to shift their body weight from one foot to the other, even when they can almost not move forward, as this is the case at very high densities.

Our results also highlight that the stepping behaviors in a crowd can be quite different from those measured in locomotion experiments with isolated pedestrians [19], though for the same range of walking speeds.

This raises some questions that would be interesting to tackle in the future. Indeed, several effects can be responsible for the change of walking behavior in a crowded environment. Walking very close to other pedestrians induces physical constraints that obviously have to be taken into account in the stepping strategy. However, at high densities, another effect comes from the presence of stop-and-go waves: pedestrians may have different step characteristics depending on whether they are accelerating, decelerating, or walking at constant pace. Even the anticipation that the pedestrian will have to accelerate in the near future could modify his behavior. It would be interesting to design new experiments to discriminate between these various effects, taking also into account the relative height of interacting pedestrians, and distinguishing the inter- and intrapedestrian variations.

Another question that we have addressed in this paper is whether pedestrians walk in lock step at high densities [4]. Indeed, at high densities, beyond 1.25 ped/m, we have observed some synchronization between the step cycles of successive pedestrians. This can be easily explained by the strong steric constraints that occur at these densities. Surprisingly, synchronization is still observed—though less frequently—at much lower densities. It seems that even when pedestrians are more than 2 m apart, they still have the tendency to synchronize their rhythm, probably as a consequence of the visual stimulus given by the pedestrian ahead. Besides, in the absence of steric constraint, we observed that synchronization and antisynchronization are both observed at such low densities.

Interest in the synchronization phenomena also stems from the observations that music can induce particular stepping behaviors. In Ref. [15], experiments in which pedestrians were asked to synchronize their steps with the indicated rhythm were reported. It was shown that it was more efficient to indicate the rhythm with music than with a simple metronome [15]. In Ref. [12], it was found in an experiment that when pedestrians walking in line are asked to walk with a rhythm (given by a metronome) slower than the natural pace of pedestrians, the flow in the congested regime is improved, as a result of the synchronization of steps. It would be interesting to investigate this further, and in particular to determine the relation between the improvement of the flow and the fraction of the pedestrians "synchronized" with the rhythm.

There would be a practical interest in knowing whether such synchronization would occur when the music is just used as a background, without any special assignment, and also what would be the consequence on the macroscopic characteristics of the flow. Further investigations are needed. It would be necessary to perform new experiments with tracking methods such as the one described in this paper, to measure in particular the amount of step synchronization between pairs of successive pedestrians. If it was shown that a musical background can improve the flow, this could be used in particular as a strategy to improve evacuation.

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