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Experimental evidence of the "Faster Is Slower" effect

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Abstract

The Faster-Is-Slower effect (Helbing et al (2000)) is an important instance of self-organized phenomenon in pedestrian dynamics. Despite this, an experimental demonstration is still lacking. We present controlled tests where a group of students are asked to exit a room through a door. Instead of just measuring the evacuation times, we have analyzed the probability distribution of the time lapses between consecutive individuals. We show how it displays a power-law tail. This method displays clearly the Faster Is Slower effect, and also allows to assess the impact of several tactics that can be put in place to alleviate the problem.

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1. Introduction

It is a known fact that an increase in the density of pedestrians does not necessarily lead to a larger flow rate (Weidmann (1993)). This result is embodied in the fundamental diagram, in which the flow is plotted against pedestrian density (Seyfried et al. (2005); Chattaraj et al. (2009)). These plots show how flow grows with density up to a certain threshold; but from there on, a further density increase leads to a decrease in the flow rate. This fact is a clear instance of how an enhanced input can actually be detrimental for the output. In the case of vehicular traffic (which certainly belongs to another context, because cars do not push one another), a similar phenomenon can take

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place (Helbing (2001)). In yet another situation, if people push harder when trying to exit a room through a door, the evacuation time can actually increase; this is called the Faster Is Slower effect. Although anecdotal evidence of Faster Is Slower in pedestrians can be gathered from recordings of human stampedes and other catastrophes, much knowledge about this outcome has been obtained from numerical simulations, because potential injuries rule out provoking panic in persons to perform an experiment. One such model is the so-called Social Force Model (Helbing and Molnar (1995); Helbing et al. (2000)). In this scheme, as in some others, the desired velocity of pedestrians is one of the parameters. Arguably, the desired velocity will increase as conditions in the room worsen and people yearn to leave it. The signature of Faster Is Slower in simulations is therefore a minimum in the plot of the evacuation time vs. desired velocity, or alternatively, for stationary systems, a maximum in the flow rate vs. desired velocity (Schadschneider et al. (2002), Kirchner et al. (2003), Hoogendoorn (2004), Parisi and Dorso (2007), Yamamoto et al. (2007), Suzuno et al. (2013)). The key notion is that at some point, an increase in the urge to leave the room will worsen the evacuation dynamics of pedestrians. Evacuation is, of course, a main concern in architectural design (Gwyne and Kuligowski (2009), Kobes et al. (2010), Zheng et al. (2009)).

A general account of why this happens can be found in the framework of the physics of granular materials (Parisi and Dorso (2005); Parisi and Dorso (2007); Lozano et al. (2012), Arévalo et al. (2014)). Of course, a direct extrapolation from the case of inert particle flows to pedestrians is unwarranted and probably misleading. Nevertheless, certain resemblances have been identified in both scenarios –such as the beneficial effect of an obstacle in front of the exit (Kirchner et al. (2003), Zuriguel et al. (2011), Shiwakoti et al. (2011))– suggesting that some general concepts may be applicable. Indeed, clogging seems to take place due to the formation of arches (mechanically stable structures of elements that are capable of arresting the flow). An array of pedestrians can get stuck at the door forming such an structure. Maybe arches in this case are unstable and unlock by themselves, due to intrinsic fluctuations in the system. These arches may be more stable when loaded, as is the case with architectural arches, and might be shattered by so-called incompatible loads, exerted in a different direction than those driving the flow (Cates et al., 1998). It has been shown that this description of clogging is valid not only for granular matter, but also for colloids and self-propelled particles (Zuriguel et al. (2014)). These authors found that a load increase causes an enhanced resistance of the arch, so the system will be even more prone to clogging. Whether this explanation is valid for pedestrians remains to be seen, and it will be difficult to test, because forces between persons are not easy to measure.

As a matter of fact, Faster-Is-Slower has been experimentally observed in inert granular materials. The first such observation was carried out in a bidimensional, vibrated silo over an incline (Gago et al. (2013)). The component of the gravity force parallel to the plane of the silo was altered by tilting the inclined plane. In this way, the force acting on the particles, which is the counterpart to the desired velocity of pedestrians, can be changed. The flow rate at the exit orifice of the silo displayed the Faster-Is-Slower phenomenon.

It is also worth considering systems where the Faster-Is-Slower effect is not observed. Ants escaping from an enclosure where a repellent is delivered, or stressed with temperature, will not clog, and in this case faster is faster indeed (Boari et al. (2013)). The fundamental ingredient that is missing in the case of ants seems to be the fact that they don't ram into each other, therefore they do not form arches, so an increased load does not disrupt the flow.

At this point, the need for experimental evidence of Faster-Is-Slower in pedestrians becomes clear. The experiments may take the form of an evacuation drill, but of course potentially dangerous situations are precluded. Therefore, only small variations in the desired velocity may be accessible, and correspondingly small differences in the evacuation time will show, if any. The foremost value of these experiments is the proof of concept concerning the phenomenon.

In performing such an experiment, we have not only revealed the validity of Faster Is Slower, but also developed new methods to analyze data that prompted us to present the evacuation dynamics in a way that displays more clearly the danger of clogging. This description can be used to assess the effectiveness of different procedures that aim to alleviate clogs. We will first describe the experiment; then we will present the results; afterwards, a careful data analysis will shed new light on the results; and finally, some conclusions will be gathered and perspectives offered.

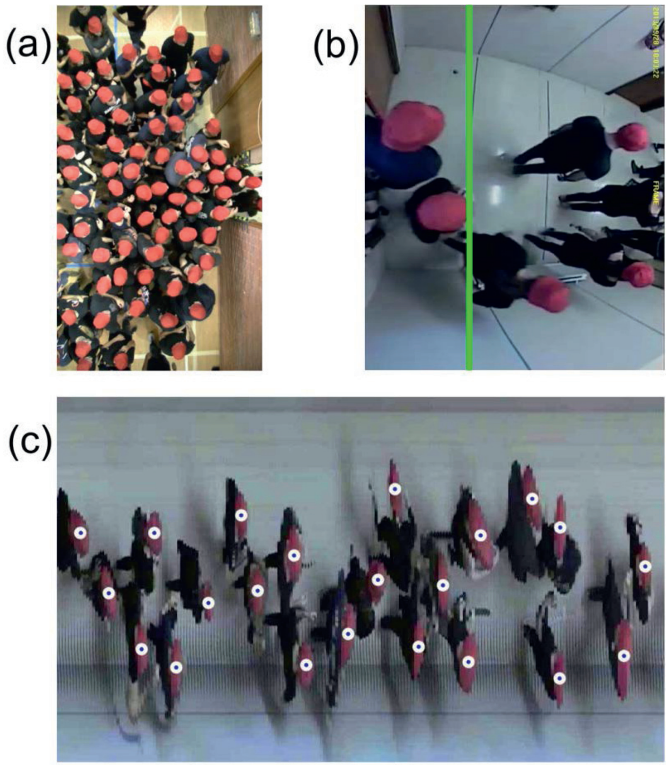

Fig. 1. Construction of an spatio-temporal diagram. (a) Picture taken inside the room. (b) Frame from the recording shot just after the door, showing the sampling line. (c) A portion of the diagram, where the centroids of the red hats worn by volunteers have been detected and marked (white circles).

2. Experimental procedures

The experiments took the form of evacuation drills. The room used is an indoor gym with a stand in the first floor that provides a convenient observation point just above the door. As we wanted a smaller exit than the existing one, we reduced the doorway width to 75 cm by placing wood planks at the sides, which were in turn covered with protective foam to avoid bruises. The door led to a wider corridor (3 m wide), and at its end another space was used as an assembly point. Standard video surveillance cameras were placed in zenithal position over the door (pointing downwards), both inside the room and outside (in the corridor).

A total of 85 students in the 4th year of the School of Architecture at the University of Navarra volunteered to perform these exercises. They are boys and girls about 22 years old. They were told to wear dark clothes and each person was given a red hat. In this way, we smoothed the way for the subsequent image processing. In order to manage the tests, and to control the procedures, four professors, two technicians and four graduate students were also present. The managing staff all carried wearable radio devices allowing two-way communication. Apart from the image acquisition cameras, other surveillance cameras were also used to monitor the tests. A control point was established on the first floor stand, from where the head supervisor gave orders by radio to the managing staff. Audible signals for the volunteers were arranged in order to start and to stop the tests. An emergency stop was also planned to be issued whenever asked for by participants or managers (for instance, a few inconsequential falls of a participant caused some tests to be interrupted). Dry runs were performed beforehand until everybody was at ease with the procedure. The evacuation drills took place safely and uneventfully.

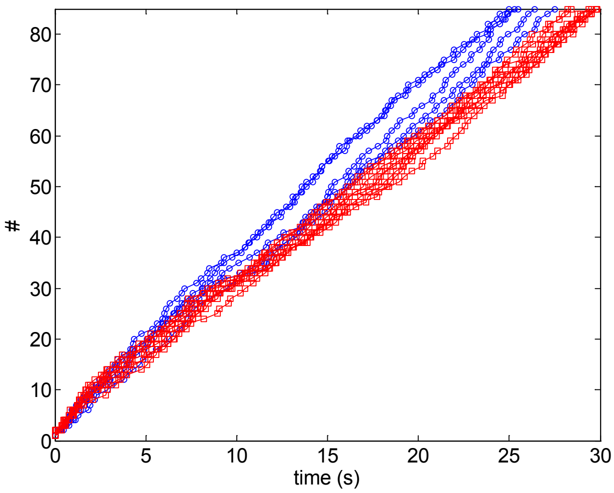

Fig. 2. Plots of the evacuation drills. Each person is represented by a point, the horizontal coordinate of which is the passage time and the vertical one the ordinal number. Blue circles correspond to non-competitive egresses and red squares to competitive egresses.

We carried out two sets of runs. In one set, students were told to exit the room as fast as they could, but without pushing or elbowing one another (in the understanding that unintended physical contact was allowed). In the second set students were told to do the same, but they were allowed to push and jostle for the exit within reason (violent shoving was of course excluded). The fact is that after a couple of dry tests the volunteers performed this quite safely and in a repetitive fashion.

Several evacuations from the room were performed during one morning (and interleaved with other tests that are not reported here). Some tests were rendered unusable due to emergency stops or other fortuitous causes. In all, we obtained recordings of five evacuation drills without pushing (from now on, non-competitive egress), and seven recordings in which moderate pushing was allowed (from now on, competitive egress).

In order to obtain an accurate timing of the exit of each participant, we built a spatio-temporal diagram from the video recordings. This is performed starting from the motion pictures taken just outside the room. A line of pixels is sampled from each frame and stacked vertically, in a procedure akin to the “photo finish” of track-and-field events. It gives an image were one axis corresponds to time and the other axis to space (hence, the name spatio-temporal diagram). We introduced a ruse to enhance the resolution. Sure enough, standard surveillance cameras yield 25 non-interlaced frames per second. As this is rather low for our ends, instead of sampling just one line of pixels we sampled five contiguous lines, thus increasing the number of lines per second in the spatio-temporal diagrams by a factor five. This does the trick, and the images were good enough to allow for the detection of the red hat centroids with a resolution of about 0.01 seconds (see Fig. 1), which is more than needed given that the average time lapse between two persons is about half a second.

In essence, what we got from the evacuation drills was an accurate time log of the student passages just after the door.

3. Evacuation time

From the data sets obtained as explained above, it is straightforward to plot the number of evacuated persons versus time (Fig. 2). It is quite obvious that competitive egress consistently produces longer evacuation times. Incidentally, fatigue or tiredness effects are discarded because the series number of the tests do not correlate with the position in the graph (i.e. longer evacuation times do not correspond to tests performed later in the morning or whatever: there is not any relationship between these two variables).

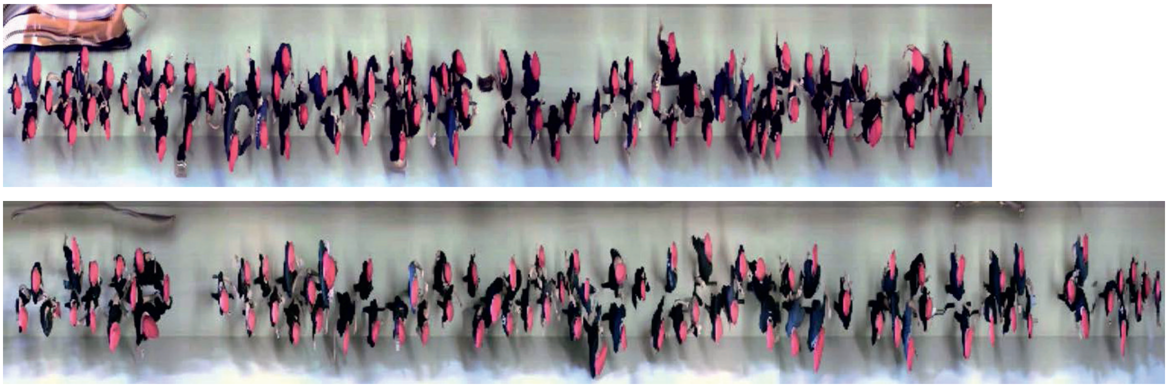

Fig. 3. Spatio-temporal diagrams corresponding to a non-competitive egress (top) and to a competitive egress (bottom). Note that they are both at the same scale.

A closer look at these plots reveals how the initial flow rate at the beginning of the evacuation is faster for the competitive egress. After inspecting the video recordings, we discovered that about ten people used to go out very quickly and unimpeded in the first few seconds. After this “transient” a “stationary regime” was reached, and the flow rate (which is the slope of the graphs) decreased below that of non-competitive exits. In these and other tests, we also observed that the last people to come out would sometimes give abnormal time lapses. In order to avoid these effects, which are due to the finite size of the sample, a good practice would be to exclude the first and last portion of the evacuation drill. The difference between competitive and non-competitive egress is in this case even more salient. We have nevertheless left the whole set untouched to provide evidence even for a finite size sample like ours.

The evacuation time can be also expressed in terms of the average evacuation time per person. In the case of non-competitive egress, we obtain $T = 0.32 \pm 0.05$ seconds per person, while for competitive egress $T = 0.38 \pm 0.04$ seconds per person. The error given is the confidence interval at 95% as calculated with a bootstrap method.

4. Time lapses

The total evacuation time needed to void a room is obviously an essential concern. But it does not fully capture the potential danger of the evacuation dynamics. In order to substantiate this statement, let us consider two typical spatio-temporal diagrams from a competitive and a non-competitive egress (Fig. 3).

The first notable difference is of course that the evacuation time is shorter for a non-competitive egress. But there is also a notable feature in the competitive exit: the voids that mark a time lapse during which nobody crossed the door, i.e., clogs. These clogs are only temporary, and the flow is restored by itself, but nevertheless the danger of such events must be recognized, because people can die owing to suffocation or crushed in a clog.

In order to analyze these events, we turned our attention to the time lapses Δt_i among two consecutive persons. Visually, the histogram of $\{ \Delta t_i \}$ seems to display a power-law tail (because when represented in a logarithmic scale, a linear trend can be seen). Nevertheless, the fit of a power law tail by simply adjusting a straight line to the histogram in logarithmic scale can be deceptive, and we used instead a rigorous method (Clauset, Shalizi and Newman (2009)). The first step is to plot the complementary cumulative distribution function, which is one minus the cumulative distribution function (CDF). The complementary CDF can be built by integrating from infinity to zero; or in an alternative picture, by ordering all the events from smaller to larger, and calculating the probability to find a Δt bigger or equal than a given value. The complementary CDF, by construction, decreases monotonically. For the first datum of the set, for instance, which corresponds to the smallest time lapse, the value of the complementary CDF is one, because all the data (the measured time lapses) are bigger or equal than it. In this representation, noise is reduced (it can be shown that it amounts to a low-pass-filter of the data), and moreover, each

Δt_i is represented by one point in the complementary CDF, so binning is avoided and the number of points available for the fit is not

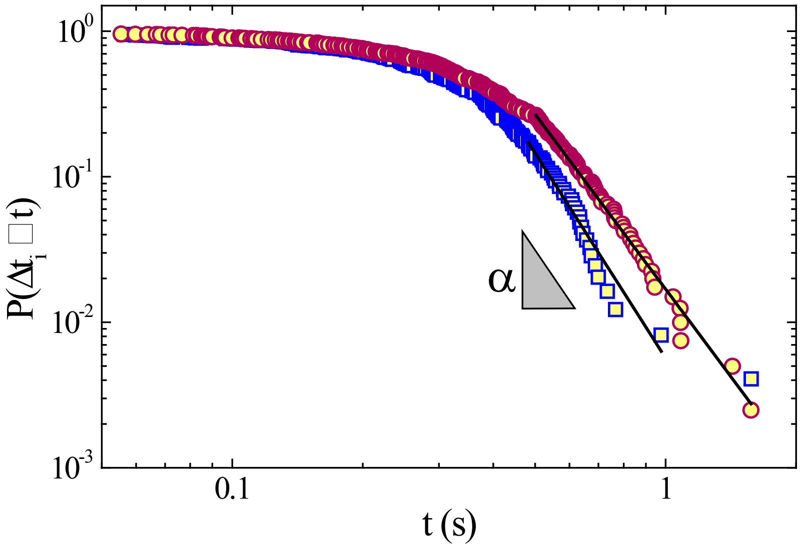

Fig. 4. Complementary CDF for { Δt_i } in non-competitive egress (squares) and for competitive egress (circles). The values of the power-law exponents are $\alpha = 5.7 \pm 0.8$ and $\alpha = 5.0 \pm 0.1$ respectively. Note the logarithmic scale. Black lines are the fits given by the algorithm proposed by Clauset, Shalizi and Newman, 2009.

reduced. A power law tail in the probability distribution function will also give a power law tail in the complementary CDF, with an exponent larger in one unity.

Usually the power laws break down for small values of the variable, due to finite size effects. For instance, if a narrow door would only allow one person at a time, so that people exit in a line, there would not be any Δt_i below a certain threshold given by the person size and the desired velocity. In our case the door is not so narrow, but the desired velocity, the door width and the person size all combine so that the power law does not hold below a certain value of Δt.

The algorithm proposed by Clauset, Shalizi and Newman (2009) involves a liner fit of the complementary CDF. It provides the value of the exponent α of the power law tail, the minimum value from which the fit is acceptable, and performs a statistical test that gives the goodness of the fit and a p-value. We have found that the fit is statistically significant for our data sets, both for the competitive egress and for the non-competitive egress –all the tests corresponding to each situation were aggregated in a single file–. This result is displayed in Fig. 4. As can be readily seen, the competitive egress displays a longer tail than the non-competitive one, meaning that it is easier to find
longer clogs (corresponding to the points at the right side of the plot). For the non-competitive egress, the power law tail decays steeply (the exponent α is large), so long clogs are statistically very unlikely.

The finding that { Δt_i } are in fact distributed according to a power law $t^{-\alpha}$ has profound implications. Unlike exponentials, a power law lacks a characteristic parameter, and this is why they are sometimes called scale free distributions. There is still a more disturbing fact, namely, that if $\alpha<2$ the average of the distribution (which amounts to calculate the first moment, an integral that extends to infinity) may not converge, giving place to an anomalous statistics (Sornette (2000)). Of course one can always calculate the average of a sample, but this average will depend on the size of the sample (number of events, duration of the observations, etc.), and it will be dominated by the largest events at the end of the tail. As the sample size increases, so do the extreme events included in it, and the average grows unboundedly.

In our case, the values of α are fairly above 2, meaning that the average of the distribution will always converge. But this is just because the evacuation drills have been performed well in the safe side, even those for the competitive situation. It is likely that a small door, a high desired velocity and a high density of people might eventually cause the exponent to be smaller than 2, in which case extreme events would appear. Hence, the mean evacuation time might not be the best measure to gauge the performance of evacuation processes. We propose instead to consider the exponent α whenever possible.

5. Conclusions

Evacuation drills have been performed in two situations: non-competitive egress, and competitive egress. We have recorded the passage of people at the exit, and by means of image analysis we have obtained the passage time for each person. In this way, we have proved the Faster-Is-Slower effect: evacuation times are consistently longer if people push harder for the exit. Apart from this phenomenon, we have also analyzed the time lapses between consecutive persons. We have shown that the distribution of time lags displays a power-law tail. The exponent of this power law is smaller for a competitive egress, meaning that longer time lapses are more likely to appear. This implies that dangerous clogs will be more probable. Although it has not been observed here, it might arrive that an anomalous statistics, dominated by extreme events, is reached. Therefore, the description of the evacuation dynamics in terms of time lapses, and the fitting of a power law tail to the distribution, provides a convenient and rigorous way to assess the condition of the process. Application of this procedure to other systems seems feasible (Zuriguel et al. (2014)).

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