Universal counterclockwise motion in human walking

Iñaki Echeverría-Huarte[1*], Claudio Feliciani[2], Zhigang Shi[3], Katsuhiro Nishinari[2], Angel Sánchez[4,5], Angel Garcimartín[1], Iker Zuriguel[1]

[1*]Departamento de Física y Matemática Aplicada, Facultad de Ciencias, Universidad de Navarra, Pamplona, E-31080, Spain.
[2]Department of Aeronautics and Astronautics, School of Engineering, The University of Tokyo, Tokyo, 113-8656, Japan.
[3]State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, 230027, China.
[4]Grupo Interdisciplinar de Sistemas Complejos (GISC), Departamento de Matemáticas, Universidad Carlos III de Madrid, Leganés, 28911, Spain.
[5]Instituto de Biocomputación y Física de Sistemas Complejos (BIFI), Universidad de Zaragoza, Zaragoza, 50018, Spain.

*Corresponding author(s). E-mail(s): iecheverriah@unav.es; Contributing authors: feliciani@g.ecc.u-tokyo.ac.jp ; 17801052163@163.com; tknishimail.ecc.u-tokyo.ac.jp; anxo@math.uc3m.es; angel@unav.es; iker@unav.es;

Abstract

Pedestrian walking behaviour is intrinsic to individuals, yet it is influenced by external factors such as obstacles and the degree of crowding. It is precisely in crowded scenarios that pedestrian interactions lead to remarkable collective motions, such as lane formation or waves. Recently, the spontaneous development of collective counterclockwise motion has been reported in both dense and sparse human assemblies. Here, we present five experimental studies of this phenomenon across diverse conditions and cultures, demonstrating that counterclockwise bias is universal and originates from individual tendencies rather than from collective interactions. These findings challenge the traditional view that social dynamics shape pedestrian motion, highlighting the existence of an intrinsic locomotor bias. While the biological roots of this behaviour remain unclear, our study deepens our understanding of pedestrian dynamics and opens new avenues for optimising crowd management by considering individual biases.

Introduction

Anyone who has walked along a crowded street has probably noticed that pedestrians spontaneously self-organise into lanes. The explanation for this phenomenon is straightforward: to avoid collisions with people approaching head-on, individuals tend to follow others who move in the same direction, eventually leading to the formation of lanes of people walking in the same direction [1–3]. This behaviour improves the average pedestrian flow and reduces personal discomfort within the crowd, as the risk of collision is minimised. For this reason, pedestrian lane formation can be seen as an example in which the crowd induces individual behavioural changes that lead to an overall benefit for the group [4]. Another scenario in which collective patterns emerge is when a crowd exits through a narrow passage—so small that two people cannot pass through it simultaneously [5]. In this scenario, pedestrians naturally split into two alternating streams—one passing through the door's right-hand side and the other through its left-hand side. This so-called "zipper effect" results in a more efficient evacuation than if they had simply formed a single file and exited the room through the centre of the door [5, 6].

Interestingly, in both cases (cross-flow and bottleneck flow) self-organised structures form owing to individual collision-avoidance manoeuvres and an unspoken mutual communication between people [7]. In other words, a simple individual behaviour adopted independently by many people can result in a collective behaviour that is only indirectly the outcome of each individual's action. This is what is called an "emerging phenomenon", with examples in pedestrian dynamics extending to group oscillations [8, 9], stripes [10, 11], and waves [12] observed in large, dense crowds. Remarkably, all these phenomena occur without any leader orchestrating them, and people are often not even aware of the pattern they are creating.

Furthermore, it has been argued that, under some circumstances, a seemingly collective pattern is created (or strongly influenced) by biased preferences of the members of a crowd. For example, in most countries, the lanes described earlier tend to form to the right (in the sense of the march) as a result of a weak tendency for people to move rightwards when facing another pedestrian [13]. Similarly, it has recently been proposed that a slight preference among right-handed people to turn left when facing a wall [14] could underlie the emergence of collective counterclockwise (CCW) crowd motion, both in mosh pit dancing [15] and when a crowd walks freely within an arena [16].

In contrast to this view, our study offers a different perspective on the origins of CCW motion. Through five carefully designed experimental campaigns conducted in diverse settings and across different countries, we have gathered compelling evidence that challenges the conventional interpretation. Rather than being an emergent property driven by interpersonal interactions (possibly influenced by personal biases), our results indicate that the collective CCW turning is rooted in inherent individual tendencies. As we shall see, we observed that CCW motion consistently emerged even when all pedestrians roaming in an enclosed space were left-handed or when their turning preference was to the right (Fig.1a). We also ruled out the possibility that the cause is associated with interactions with boundaries by conducting experiments in an open space (Fig.1b). Another plausible hypothesis related to interpersonal interactions—in particular, to avoidance manoeuvres—suggested that such manoeuvres might trigger CCW rotation in the same way as they lead to right-side lane formation in counterflows. However, the results from experiments in Japan (Fig.1c), where lanes tend to form to the left side (in the sense of the march) during counterflows, refuted this idea. Moreover, we excluded social or acquired cultural influences (such as the CCW sense of motion in athletics tracks) by analysing the dynamics of children during free play at a Japanese nursery (Fig.1d) [17]. We also disproved the possibility that some unspoken social norm could be responsible for CCW motion by showing that no such norm exists. Finally, we analysed single pedestrians walking alone in an enclosure, confirming that this symmetry-breaking phenomenon is caused by individual behaviour, most likely biologically rooted.

Our contribution is thus twofold. First, we provide robust experimental evidence showing that the CCW bias is a universal characteristic of human locomotion, observable even in isolated trials. Our findings demonstrate that the symmetry-breaking phenomenon arises from innate individual predispositions, while ruling out the most obvious explanations—such as handedness, footedness, and eye dominance—thus leaving the precise origins open for further investigation. Second, by demonstrating that this intrinsic bias exists independently of the collective context, we deepen the current understanding of pedestrian dynamics. Our findings suggest that nontrivial group behaviours can originate from basic individual locomotor predispositions, opening new avenues for research and practical applications in areas such as urban planning and crowd management.

Results

In this section, we present our results about the statistical properties of motion observed in each experiment. By analysing the patterns and differences across different scenarios and countries, we aim to uncover the underlying mechanisms driving the consistent CCW asymmetry in human motion and offer explanations for its prevalence.

Confined Random Motion in Spain

Our first study was carried out in Spain with the aim of corroborating that CCW motion is caused by a small bias in the turning preference of pedestrians when facing a wall (right-handed people prefer turning towards the left [14]). Under this premise, we implemented experiments in which groups of people with different handedness and turning preferences were asked to roam a 5-meter radius circular arena (Fig. 1a). The turning preference of each participant was identified before the group trials. To this end, each volunteer was instructed to walk along a straight line until reaching a wall, execute a 180-degree turn, and return. In this way, individuals were categorized as either Right-Turners (RT) or Left-Turners (LT) depending on their turning direction. Independently, volunteers who were both left-handed and left-footed were categorized as Left-Dominant (LD).

In each experiment, participants moved freely within the arena for three 40-second intervals interspersed by two phases in which they were asked to navigate to a designated point. These distinct movement phases are clearly identifiable by analysing the temporal evolution of the average velocity of the group (inset of Fig. 2, upper panel). Free movement periods (highlighted in colour) display a notably higher speed than the beginning of the experiment or the directed movement phases (in grey). To quantify the directionality of rotation, we employed the polarization parameter M (see *Methods* for the definition), which quantifies the average alignment of motion of all pedestrians relative to a central point [18]. At each time step, the polarization of the ensemble M was computed as the average of all the individual pedestrian polarizations m_i. An example of the temporal evolution of $M(t)$ is depicted in the inset of Fig. 2 (lower panel). To quantify the system's net rotational tendency, we computed the time-averaged polarization $\overline{M}$ during each interval of free motion. $\overline{M} > 0$ corresponds to CCW motion, whereas $\overline{M} < 0$ indicates clockwise (CW) motion.

As explained, it was expected that increasing the proportion of RT in the experiment would favour CW rotation. But the results revealed that neither the number of participants nor the proportion of RT significantly influenced $\overline{M}$. Instead, across all experimental conditions, $\overline{M}$ consistently exhibited a positive value around $\overline{M} \sim 0.2$ (Fig. 1e, orange), indicating a robust and persistent CCW bias. In this sense, it is noticeable that even experiments A1 and A11 (in which 100% of pedestrians were right turners and left-handed, respectively) revealed a similar, positive value of $\overline{M}$.

To further understand this observation, we analysed the probability density functions of M (Fig. 2). Interestingly, regardless of the global density (increasing from a to c) and the RT proportion, all distributions are shifted towards positive values and are unimodal with the peaks centred at $M \sim 0.25$. The low proportion of $M < 0$ values implies that the system maintains a constant CCW rotation. At the same time, the absence of values at $M \sim 1$ indicates that the CCW motion is not a global effect involving all pedestrians. Interestingly, the distributions become narrower as the number of pedestrians increase, which may suggest the existence of a collective effect that boosts the stability and robustness of the CCW rotation. More importantly, the overlap of all distributions obtained with the same number of pedestrians (especially for large crowds) indicates that individual turning preferences have a negligible impact on the emergence of CCW behaviour.

Next, aiming to elucidate the actual role of boundaries in the development of CCW motion, we analysed the spatial distributions of density, velocity, and polarization within the arena (Fig. 3). The density fields (first row, Fig. 3) show a rather homogeneous spatial distribution, yet some faint circular patterns can be perceived. The velocity fields (second row, Fig. 3) reveal that the CCW motion extends over the whole arena but is a little bit more pronounced near the boundaries. This is further confirmed by examining the polarization fields (third row, Fig. 3). On average, bluish regions are more abundant over the whole arena, but the colours are more intense near the boundaries; hence suggesting a possible role of those in the development of CCW rotation.

Boundary-Free Experiment in a Schoolyard

From previous results, and in order to clarify if the boundaries really trigger the CCW motion or just help to stabilize (and perhaps magnify) it, we designed a follow-up experiment in which pedestrians walk in an open and practically unconstrained setting (Fig. 1b). This consisted of a

$50 \times 60\,\mathrm{m}^2$ schoolyard in Spain, where over one hundred teenage students were gathered (see *Methods* for details). Surprisingly, despite the influence of boundaries being practically suppressed, the CCW rotation persisted as reflected by the positive value of $\overline{M}$ depicted in Fig. 1e (red). In agreement with this, the analysis of the PDF(M) reveals again a unimodal distribution shifted towards positive values (Fig. 4a). Interestingly, the PDF(M) is even narrower than the ones presented in Fig. 2, suggesting that the variable controlling the width of the distribution is the total number of pedestrians; and not the density – which in this case is 6 times lower than in the sparser experiments of the first scenario.

Confined Random Motion in Japan

After ruling out the pedestrian-boundary interactions as the origin of the CCW rotation, we focused on pedestrian-pedestrian interactions as a potential driving mechanism. Pedestrian-pedestrian interactions are key to various self-organizing behaviours, with lane formation in bidirectional flows being a prime example [4, 19, 20]. This process arises from local coordination, where individuals adjust their paths during head-on encounters to avoid collisions [21]. In Spain (and most European countries), this avoidance manoeuvre is typically implemented by moving towards the right-hand side [13, 22], hence leading to the symmetry breaking in lane formation. After this fact, the hypothesis was that if pedestrians avoid collisions giving way by a motion towards the right side (thus leaving the incoming person to the left), in the circular arena they would end up moving CCW near the boundary.

To test this idea, we conducted experiments in Japan, a country where lanes in bidirectional flows conspicuously appear on the left side, as pedestrians generally avoid others by stepping to the left. First, we confirmed this left-side stepping tendency through a questionnaire where participants indicated their natural avoidance direction when viewing corridor walking images (see Supplementary Section A for details). We then performed new experiments in an enclosure similar to the one used in Spain (Fig. 1c), and following the same methodology. Unexpectedly, the positive values of M reported in Fig. 1e reveal that the CCW motion persisted, hence refuting the idea of the stepping aside pedestrian manoeuvres being behind the collective development of CCW motion. Indeed, $\overline{M} > 0$ in all experimental trials but one (C9 in which $\overline{M} \approx 0$), an exception which we might put down to the intrinsic variability of human behaviour. Furthermore, as already observed in experiments 1 and 2, the distributions of M (Fig. 4(b-c)) remain skewed towards positive values and the peak (at about $M \sim 0.2$) is more marked as the number of pedestrians in the arena increases; i.e. the fluctuations of M are smaller as the population size grows.

Random Motion in a Nursery School

We then addressed the question of whether social rules or learned behaviours – potentially shaped by sport events like athletics or cultural practices – might be the cause of the CCW collective motion. To explore this option, we analysed experiments implemented in a nursery school as it can be assumed that, in principle, young children are less likely to be affected by social influences [23]. In these experiments, conducted by Ichikawa et al. (Fig. 1d) [17], children (about 5 years old) participated in an eurhythmics activity involving free running (see *Methods* for more details). Interestingly, the CCW motion not only develops as in previous scenarios, but it becomes much more patent as revealed by the higher values of $\overline{M}$, systematically above $\overline{M} = 0.7$ (Fig. 1e, green). This behaviour is corroborated by the distributions of M (Fig. 4d) which show a noticeable peak near $M \sim 1$ that indicates a highly consistent and stable vortex-like motion, with all children moving in unison. This suggests that children, at least in this specific activity, tend to imitate their peers and end up walking in the same direction which, of course, is the CCW one.

Social Norm Elicitation

Subsequently, we considered the possibility that unknown social norms were behind the emergence of CCW motion. We used the notion of social norm introduced by Bicchieri [24], which arises from the consideration of the expectations of people about a given situation. Two kinds of expectations are taken into account. Empirical expectations (often referred to as descriptive norms [25]) correspond to what individuals think others in their reference group will do when faced with the situation of interest. Normative expectations (also called injunctive norms) refer to what individuals think the rest of their reference group expects them to do. Normative expectations are generally accompanied by the assumption that if individuals do not conform to the expected behaviour, they will be sanctioned or punished in a number of different ways. In this framework, we say that a social norm in a group exists if the majority of people in the group share common empirical and normative expectations, and the two types agree on the behaviour to be followed. Expectations are then elicited by means of a questionnaire [26]. In our case, this test was composed of three different questions which allowed us to identify the personal beliefs (Q1), the empirical expectation (Q2) and the normative expectation (Q3) of participants (see *Methods* below). This survey was performed in Spain with a group of 168 participants.

The results of this study are presented in Fig. 5. Panel (a) illustrates the hypothetical scenario shown to the survey respondents, while panel (b) summarizes their responses. As can be seen, if a social norm is indeed present, it would surprisingly be to move CW: nearly 40% of respondents exhibited aligned empirical and normative expectations in the CW direction (i.e., Q2 and Q3 both indicated CW) and also reported a personal inclination to move CW (Q1), while another 15% of the participants also shared those expectations even if they would move in the CCW direction. This must be compared to roughly 20% of respondents who expect to move CCW, while approximately 25% provided conflicting answers. Therefore, we must conclude that a clear norm does not exist but, in case we would accept a little bit more than the majority's expectations as a norm, it surprisingly would go against the observed behaviour.

Individual Behaviour

Thus far, the analysis of collective polarization M across different experiments has demonstrated the universality of the CCW rotation effect. Moreover, the distributions of M revealed that this effect persists over time, with fluctuations around the average being dependent on the total number of pedestrians and not on the density of them. More importantly, the absence of values at $M \sim 1$ in all the systems but in the Japanese nursery school, indicates that the CCW motion is not a global effect involving all pedestrians. This seems reasonable as pedestrian behaviour exhibits inherent variability and, although on average the collectivity is always rotating CCW, there might be individuals moving in the opposite direction.

To quantify this, we took advantage of our experimental capabilities, which enable precise tracking of each pedestrian, and analysed individual behaviour using the individual polarization parameter m_i. Unlike M, which captures collective motion, m_i quantifies each pedestrian rotation pattern, providing insight into the individual behaviour. As an example, in Fig. 6(a-d) we illustrate four typical trajectories from the Japan experiment together with their corresponding PDF(m_i) (Fig. 6(e-h)). Fig. 6a displays a very stable CCW trajectory characterized by a unimodal and sharply skewed distribution that peaks near $m_i \sim 1$; in much the same way, Fig. 6b corresponds to a very stable CW trajectory. Fig. 6c exemplifies another type of pedestrian behaviour in which the rotating direction changes during the experiment (in this case, it changes twice). Accordingly, the PDF(m_i) shows a bimodal distribution with two marked peaks at $m_i \sim 1$ and $m_i \sim -1$. Finally, Fig. 6d shows a scenario in which the pedestrian rotates, but also performs a number of straight paths that give rise to more values of m_i different from ± 1, and therefore to a broader distribution.

Considering the particularities of these distributions and aiming to reflect the individual behaviour using a single parameter, we computed the time-averaged individual polarization ($\overline{m_i}$) for each pedestrian. In this way, $\overline{m_i} \sim 1$ corresponds to pedestrians walking always CCW, $\overline{m_i} \sim -1$ corresponds to pedestrians walking always CW, while intermediate values (and particularly, those close to $\overline{m_i} \sim 0$) reflect both, pedestrians that change rotating direction as in Fig. 6c and those performing straight trajectories as in Fig. 6d. In Fig. 7 we represent the distributions of $\overline{m_i}$ for all pedestrians that participated at each experiment (note that, for each experiment, we combined the results obtained in different conditions). Remarkably, in all cases the distributions show a notorious peak at $\overline{m_i} \sim 1$, revealing the presence of a number of people determinedly walking CCW, no matter the specific conditions at which the experiment was implemented. Also, the distributions suggest the existence of an analogous peak at $\overline{m_i} \sim -1$, but this is in general less prominent and altogether absent in the case of the nursery school experiments.

Overall, Fig. 7 provides strong evidence of substantial individual variability in rotational behaviour. Despite this variability, in all experiments there is an important proportion of pedestrians exhibiting a determined preference for CCW rotation. Notably, this behaviour at the individual level helps to explain the main features reported for the collective polarization parameter M. In this way, the consistent positive values of M can be justified by the presence of a larger proportion of pedestrians moving CCW than CW. Similarly, the absence of a peak at $M \sim 1$ can be explained by the intrinsic variability of the pedestrian type of motion; with the exception of kids, in all cases there will be people walking CW or straight. Also, the findings reported in Fig. 7 suggest that the correlation among the sharpness of the PDF(M) and the crowd size is merely a statistical effect. When the crowd is small, each value of M is computed using a small number of values of m_i, and then the fluctuations increase just for statistical reasons.

Beyond this nice correlation among the macroscopic behaviour and the individual one, the results of Fig. 7 suggest that the prevalent preference for CCW rotation is not a collective effect but an individual one. Interestingly, this hypothesis is supported by the fact that the distribution with the sharpest peak at $m \sim 1$ occurs for the scenario in which pedestrians move with more freedom; i.e. the teenagers walking in a space free of boundaries (Fig. 7b).

Individual Motion

Aiming to confirm that the CCW motion symmetry breaking is not caused by a collective effect but a result of individual preferences of motion, we implemented a new set of experiments in which over 200 participants walked alone (one at a time) in an enclosed arena (Fig. 8a). In these new tests, we looked for a connection between this hypothetical CCW motion preference of the individuals and some biological features, such as handedness, footedness, or eye prevalence. To this end, each participant was asked about their dominant hand, foot, and eye (left or right). If they were unsure, dominance was determined through a series of performance tests (see *Methods* for details). Participants who showed no clear dominance (i.e., were ambidextrous or had indeterminate eye preference) were excluded from the analysis. Furthermore, 49 participants were asked to walk with a patch covering the right eye, a strategy that was aimed at evaluating whether compromising the eye laterality could have a significative effect on the rotational bias.

For each pedestrian, we extracted the complete trajectory within the arena (left panels of Fig. 8b) and obtained the instantaneous individual polarization $m_i(t)$. Then, we computed the probability density function of the polarization values of each individual. In the right panels of Fig. 8b, we show two examples corresponding to a pedestrian who is consistently walking CCW (top panels) and a pedestrian with several changes in the rotation direction (bottom panels). From these distributions, we calculated $\overline{m_i}$ for each pedestrian, and then built the distributions of PDF($\overline{m_i}$) (as in Fig. 7) by considering all participants, irrespective of their condition. Clearly, the distribution exhibits a pronounced peak near $\overline{m_i} \sim 1$, much higher than the one at $\overline{m_i} \sim -1$. This result definitively proves that the origin of the CCW motion is not at the crowd level, but at the individual one. Interestingly, the distribution also presents a peak for values of $\overline{m_i}$ slightly greater than 0 that is more prominent than for the individuals moving within a crowd (Fig 7). We speculate that this might be related to psychological aspects as moving in an empty space with no other pedestrians might become unengaging, hence provoking the change in the rotation direction of pedestrians as in Fig. 8b bottom panels. Anyway, the notable result of Fig. 8c is that the CCW asymmetry exists at the individual level. In order to statistically validate it, we performed a one-sample Wilcoxon signed-rank test against 0: $z = -5.63$, $n = 156$, $P < 0.001$, $r = -0.45$, 95% CI = 0.12 − 0.26. This result confirms that the median of the distribution is significantly different from 0, and therefore the CCW bias is a robust feature of individual motion.

Next, we grouped the data according to pedestrian particularities such as handedness, footedness, eye dominance, and gender. Also, we discriminated the pedestrians who were asked to use a patch over their right eye. As shown in the box plots of $\overline{m_i}$ in Fig. 8e, the CCW bias remains consistent across all subgroups. Mann–Whitney U-tests further confirmed no significant differences in $\overline{m_i}$ between right- and left-handed participants: $U(142, 14) = 898$, $z = -0.60$, $P = 0.554$, $r = -0.05$, 95% CI = -0.33 − 0.18, between right- and left-footed participants: $U(138, 18) = 1134$, $z = -0.60$, $P = 0.553$, $r = -0.05$, 95% CI = -0.22 − 0.10, between right- and left-eyed participants: $U(96, 60) = 2851$, $z = -0.11$, $P = 0.917$, $r = -0.01$, 95% CI = -0.15 − 0.12, or between male and female participants: $U(62, 94) = 2542$, $z = -1.35$, $P = 0.178$, $r = -0.11$, 95%

CI = -0.24 – 0.03. Likewise, restricting the analysis to participants with right-eye dominance revealed no meaningful difference in $\overline{m_i}$ between those who wore a patch and those who did not: $U(156, 49) = 4385$, $z = 1.32$, $P = 0.188$, $r = 0.12$, 95% CI = -0.05 – 0.26.

Together, these results support the hypothesis that the CCW motion bias arises from individual locomotion trends rather than group-level phenomena. Remarkably, this intrinsic breaking of symmetry does not seem to depend on any of the laterality-related biological features considered in this study. Going a step further, we try to connect the individual motion results with the distributions of collective polarization (Figs. 2 and 4) and the observed enhancement of the peak with the crowd size. As was mentioned above, one could attribute this result to a collective effect; however, in Fig. 8d we demonstrate that the same behaviour is obtained by constructing the PDFs from randomized samples of individual pedestrians moving alone (as shown in Fig. 8b). For each crowd size, we randomly select a subset of individuals and take one polarization measurement from each to calculate the hypothetical group-average polarization, $\tilde{M}$. We repeat this process for 1000 subsets, obtaining a statistically robust distribution of $\tilde{M}$ values as shown in Fig. 8d. Importantly, from data obtained for pedestrians walking alone, we obtain synthetic distributions of global polarization that peak at $\tilde{M} \sim 0.25$ and become systematically narrower as the crowd size increases; exactly as it happened with the distributions of collective polarization. This finding corroborates the idea that the individual preferences of motion are likely the most important features observed at the collective level.

Discussion

In this work, we have implemented a series of experimental realizations—conducted in diverse conditions and across different cultural contexts—that conclusively demonstrate the universality of CCW motion. Our findings are robust: regardless of crowd size, boundary effects, or laterality traits such as handedness, footedness, and eye dominance, CCW motion consistently emerges. This reproducibility across varied settings, including two countries with different social norms and experiments with adults and children, supports the strength and reliability of our findings.

Traditionally, emergent collective behaviours in pedestrian dynamics have been attributed solely to local interactions and social coordination [27, 28]. However, our data reveal that the CCW preference does not arise from these interactions. Instead, our results indicate that this symmetry-breaking phenomenon is fundamentally rooted in individual locomotor tendencies. This challenges the prevailing assumption that group-level behaviours are more than the sum of individual behaviours. We have even ruled out the possibility that hitherto unknown social norms could be the cause of the CCW motion. Therefore, our work exemplifies an instance of crowd motion which can be primarily explained without the need to resort to collective effects, nor to the specificities of pedestrian interactions (among them or with the environment). Moreover, the validation of our results through carefully controlled isolated trials suggests that intrinsic locomotor predispositions are a fundamental aspect of crowd behaviour. The lack of an explanation for the origin of such individual biases opens new avenues for future research aimed at unravelling their biological or neurological grounds.

The implications of our findings are significant. By demonstrating that individual biases—rather than collective effects—drive the observed CCW rotation, our study deepens our understanding of pedestrian dynamics and provides a new lens for studying crowd behaviour. This breakthrough refines our theoretical framework while opening promising avenues for practical applications in high-traffic settings like airports, train stations, museums, and shopping centres. However, further research is needed to determine whether these individual tendencies persist in complex, real-world environments featuring static obstacles and varied pedestrian flows [29, 30]. Controlled investigations of these dynamics could ultimately enhance urban design and crowd management strategies, paving the way for innovative, people-centric public spaces.

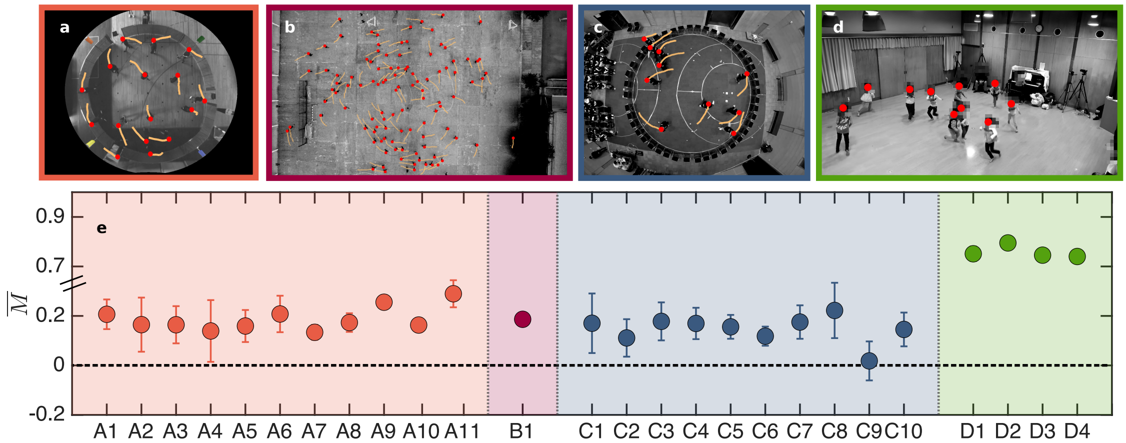

Fig. 1 Experimental setups and collective turning polarization. Panels (**a**–**d**) show snapshots of the different analysed experimental scenarios, illustrating pedestrian trajectories over the last 2 seconds (orange) and their current positions (red). **(a)** Confined random motion in Spain, **(b)** random motion of Spanish teenagers in a schoolyard, **(c)** confined random motion in Japan, and **(d)** random motion in a Japanese nursery school. Panel **(e)** shows the time-averaged collective polarization ($\overline{M}$, as defined in *Methods*) for the different experimental conditions evaluated in each scenario (see Supplementary Table I for more details). Error bars indicate the standard error of the mean.

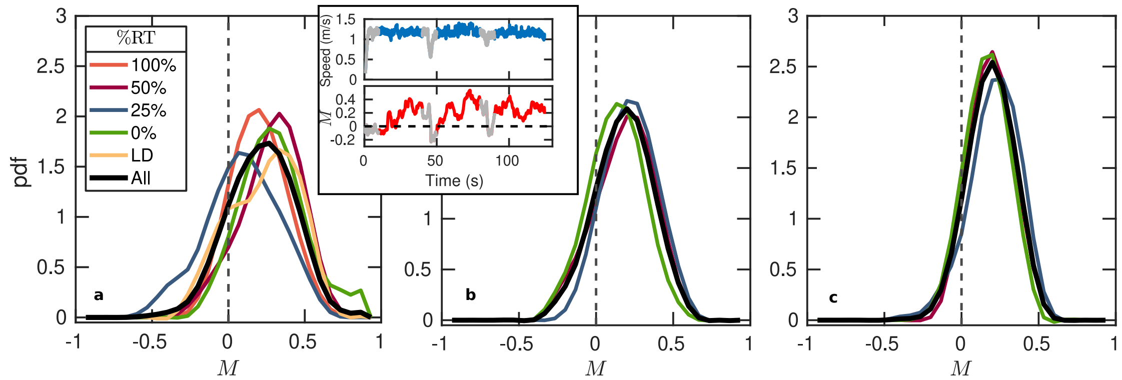

Fig. 2 Collective rotational behaviour on confined random motion in Spain. The panels show the probability density functions (PDFs) of the collective polarization values (M), for groups with different numbers of participants: **(a)** 16, **(b)** 24, and **(c)** 32. Different colours (see legend) are used for crowds with different percentages of right-turners (%RT) and for the case with only Left-Dominant (LD) pedestrians. The black line represents the aggregated distribution obtained by combining data from all experimental conditions. Inset: time series of the average speed of all participants (top) and the collective polarization (bottom). The values used to generate the PDFs are the ones marked on red. Intervals covering the initial stage of the experiment and periods of directed motion towards the walls (gray in the inset), were identified by analysing the average speed, and excluded from the analysis.

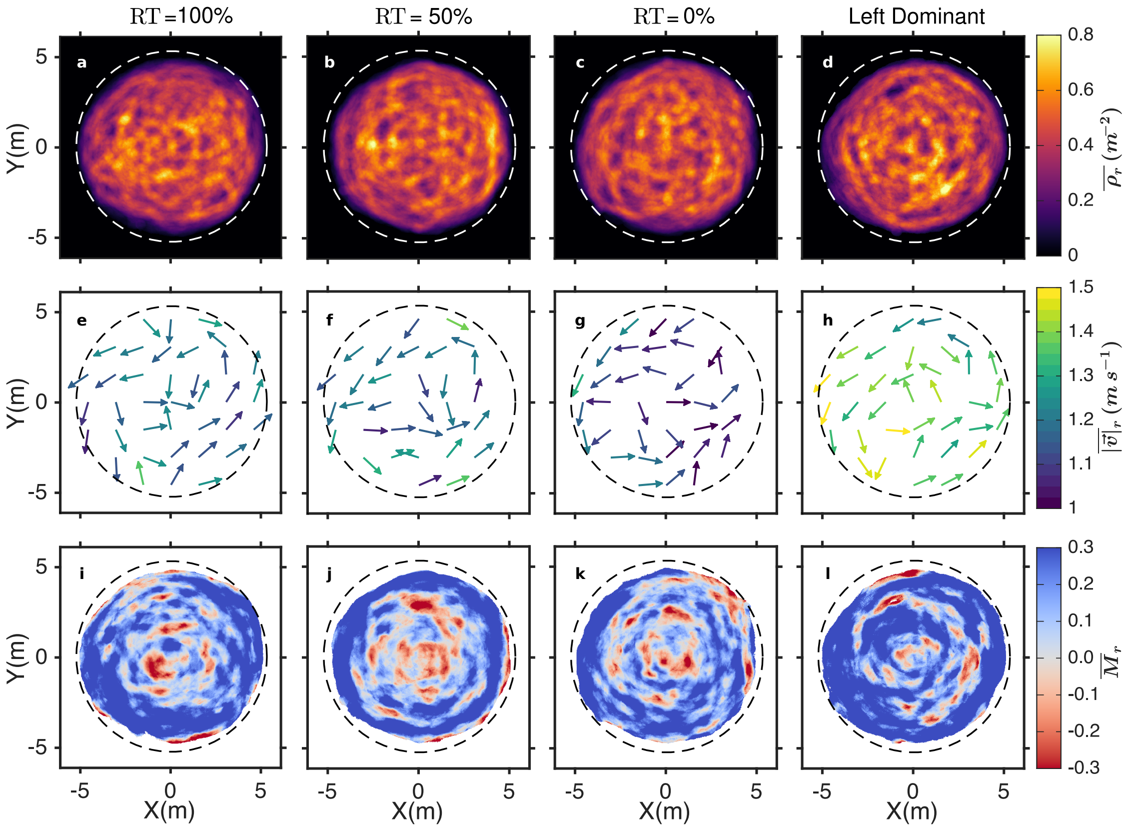

Fig. 3 Density, velocity and polarization fields for varying proportions of right-turners in the Spanish confined scenario. Spatial distribution of temporally averaged density $\overline{\rho}_r$ (first row), velocity $\overline{\vec{v}}_r$ (second row), and polarization $\overline{M}_r$ (third row) fields for a crowd of 16 pedestrians with different turning preferences as indicated at the top. The colour scales on the right (same for all cases) indicate i) the average local density in persons/m^2 **(a-d)**; ii) the average speed in m/s **(e-h)**; and iii) the average local polarization value **(i-l)**. In **(e-h)** the arrows indicate the average direction of the local velocity vector. The spatial units in both the vertical and horizontal directions are metres for all plots.

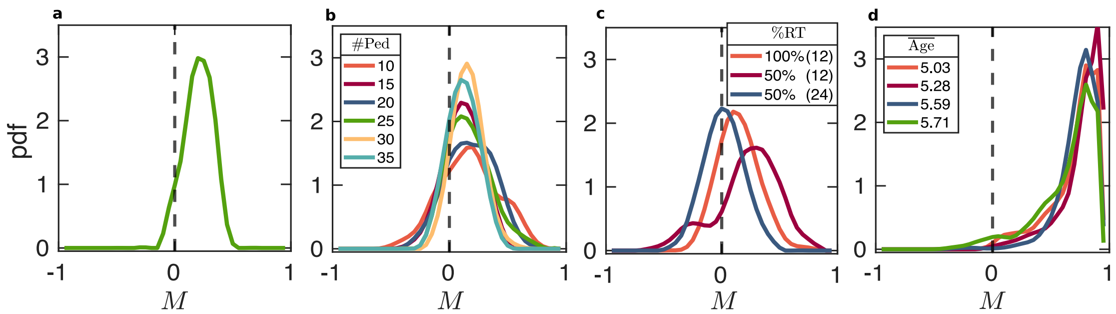

Fig. 4 Probability density function (PDF) of collective polarization values (M) in different scenarios. In **(a)** the free-boundary motion of teenagers in Spain. In **(b-c)** the confined motion in Japan. In **(d)** the kids motion in a Japanese nursery school. In each panel, colours are used to label different experimental conditions, as described in the legends. In **(a)**, only one experimental condition is considered. In **(b)**, each curve corresponds to a different crowd size. In **(c)**, both the percentage of right-turners (%RT) and the group size (12, 24) varies. In **(d)**, four realizations with different children of slightly different age are reported.

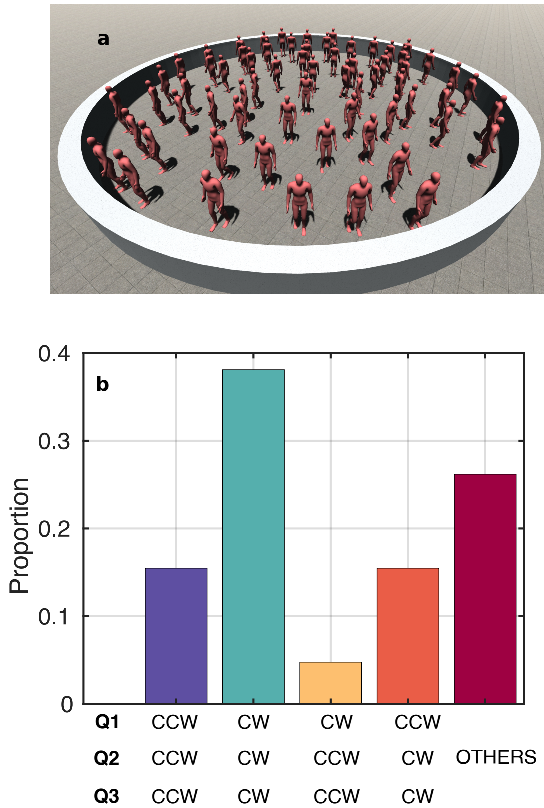

Fig. 5 Influence of Social Norms. (a) Photograph used in the survey, where participants responded to three questions (Q1, Q2, Q3) about the direction of rotation they would choose. See *Methods* for the complete survey form. **(b)** Proportion of responses to the survey questions. Answers, limited to CW or CCW, are grouped into three categories: (i) The same answer for all three questions (all CW or all CCW), indicating a strong influence of social norms, (ii) The same answers for Q2 and Q3 but different from Q1, suggesting a moderate influence of social norms, and (iii) Mixed answers, reflecting a weak influence of social norms.

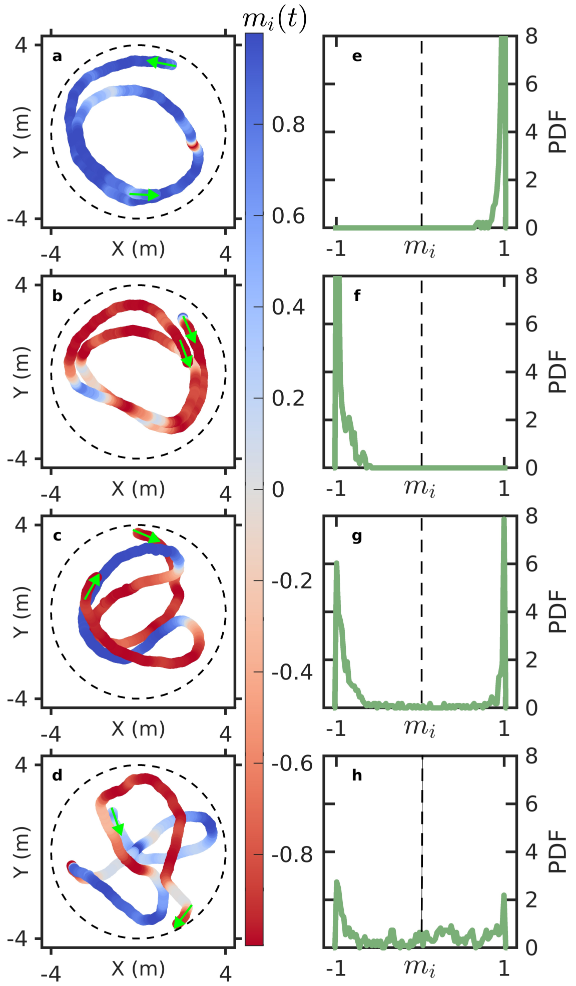

Fig. 6 Four representative cases of individual rotational behaviour during confined motion in Japan. (a-d) Individual trajectories of four different pedestrians over 40 seconds coloured according to the instantaneous individual polarization value (m_i) (see colour bar on the right). Green arrows indicate the direction of motion at the start and end of each trajectory. Spatial units in both the vertical and horizontal directions are meters. **(e-h)** The corresponding probability density functions (PDFs) of m_i for each trajectory.

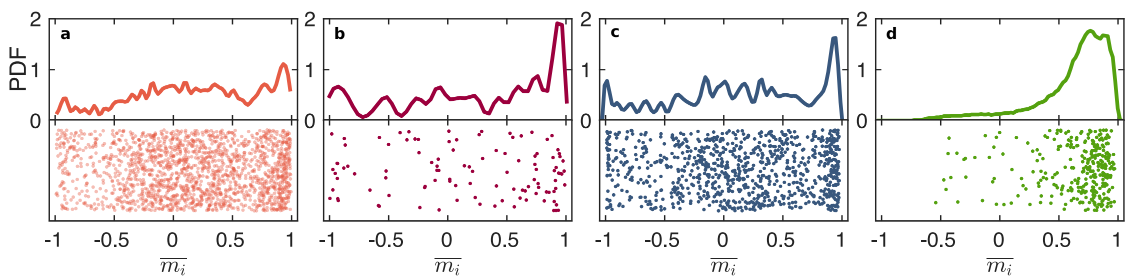

Fig. 7 Average polarization values for each pedestrian in the four studied scenarios. Each panel includes a stripchart at the bottom, showing the time-averaged polarization values for each pedestrian ($\overline{m}_i$) and the corresponding probability density function (PDF) of the whole set of these $\overline{m}_i$ values at the top. **(a)** confined motion in Spain, **(b)** free-boundary motion of teenagers in Spain, **(c)** confined motion in Japan, and **(d)** kids motion in a Japanese nursery school.

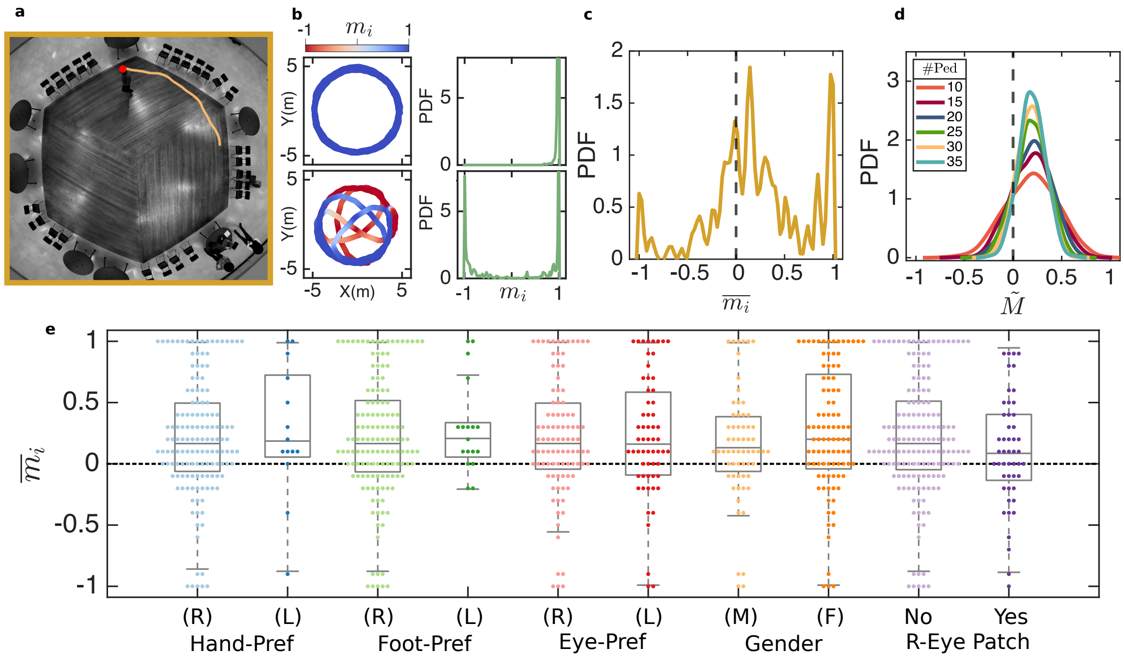

Fig. 8 **Rotational motion of individuals.** **(a)** Snapshot of the last experimental setup, where individual pedestrians were instructed to walk alone and freely within an enclosure. The recent trajectory followed by the participant is shown in orange, with the current position marked in red. **(b)** The trajectories of two pedestrians over a 60-second period are depicted, with colours representing their instantaneous individual polarization m_i, as indicated by the colour scale above. On the right, the probability density functions (PDFs) of m_i for each trajectory are shown. **(c)** Probability density function (PDF) of the individual time-averaged polarization values ($\overline{m}_i$). **(d)** Synthetic PDF of the "collective" polarization $\tilde{M}$, constructed by aggregating instantaneous individual polarization values m_i randomly selected from different pedestrians at arbitrary times. Note that $\tilde{M}$ is not a genuine collective measure, but rather a synthetic construct designed to emulate its statistical properties. **(e)** Box plots of $\overline{m}_i$ of the data grouped by individual features: handedness preference (Hand-Pref), footedness preference (Foot-Pref), eye dominance (Eye-Pref), gender, and whether the right eye is patched or not (Right-Eye Patch).

Methods

Experiments

To investigate the underlying mechanisms contributing to the CCW bias observed in pedestrian dynamics, we conducted a series of six carefully designed experiments. Each experiment was tailored to test a specific hypothesis, ranging from the effects of physical interactions in confined spaces to the influence of social norms and individual-level characteristics. The following subsections provide a detailed overview of the experimental setups, methodologies employed, participant characteristics, and procedures implemented in each study.

Confined Random Motion in Spain

The first experiment was conducted at the University of Navarra, Spain. The arena was a confined circular region of 5 meters radius, enclosed by 1-meter-high fences (Fig. 1a).

A total of 50 participants (23 men, 27 women; age 25.7 ± 4.08 years) were recruited through an online form. Informed consent was obtained from all participants prior to participation. The University of Navarra's ethics committee determined that its reviewing was not needed, as the data were anonymized from the start—no personal information was collected, and no faces were recorded during the experiments.

Upon arrival, each participant completed a preliminary task involving a walk along a marked straight line towards a wall, turning at the wall, and returning to the starting point. This task allowed us to categorize participants as left-turners (LT) or right-turners (RT) based on the direction of their turn. Based on this classification, we constructed different experimental conditions varying the number of pedestrians inside the enclosure (global density) and distinct proportions of RT. A complete description of all experimental conditions can be found in Table. I (SI).

The sequence of each experiment was as follows:

1. Initial Positioning: Participants positioned themselves at pre-marked starting points (black crosses in the ground) looking towards one of the four coloured equidistant posts that were placed outside. Importantly, the post each pedestrian was asked to look was randomly determined by an individual code provided to each participant on a card.
2. First Random Phase: Following a starting signal, participants start walking for 40 seconds. At the start of the experiment, they were instructed to move continuously without stopping and avoiding following others. The first 10 seconds of this phase were excluded from the analysis to avoid any possible transient effect.
3. Target Motion: Participants were instructed to move towards one of the four coloured posts near the fence, touch the fence close to the signal, and then resume walking.
4. Second Random Phase: Random walking resumed for another 40 seconds, with the first 10 seconds excluded due to motion transitions following the target interaction task.
5. Repeated Target Motion: Participants were prompted to repeat the action of moving to the posts (different than the previous ones).
6. Third Random Phase: Random walking continued for 40 seconds, again excluding the initial 10 seconds.

In total, three 30-second random walking intervals per experiment were analysed. Each experimental condition was repeated twice but with different individuals, resulting in six different phases of random motion to analyse.

All experiments were recorded using a camera mounted 10 meters above the ground, positioned directly above and pointing toward the centre of the arena. The footage was captured at a resolution of 4000×3000 pixels at 15 frames per second. A custom-built image analysis program was used to track the positions of all pedestrians in the videos. To correct image deformation caused by the camera, the positions were calibrated using approximately 40 images of a reference chequerboard. Velocities were calculated over a sliding window of 0.8 seconds to ensure pedestrians had moved a sufficient distance, minimizing spurious noise. A representative example of one experiment is included in the Supplementary Movie 1.

Teenagers in a Spanish Schoolyard

The experiment was conducted at the Hijas de Jesús secondary school in Pamplona, Spain. The schoolyard, measuring approximately 50×60 m^2 (see Fig. 1d), constituted the experimental area. A total of 107 students, aged 13–14 years, participated in the study. Prior to the experiment, detailed explanations of the video recording and data collection procedures were provided to the school principal and the students' parents. Informed consent was obtained from both the principal and the parents based on distributed informational materials.

In accordance with the methodology used in the aforementioned studies, participants were instructed to walk freely within the schoolyard, avoiding stopping or forming clusters. Initially, all students were gathered in a circular region marked on the ground. After the starting signal, the experiment began and lasted for 100 seconds. To avoid any potential bias due to initial positioning, the first 30 seconds of the experiment were excluded from the analysis. The remaining 70 seconds were used to evaluate the collective and individual rotational behaviours of the participants. The same experiment was repeated twice.

A DJI drone was used to capture footage from a height of 40 meters. The recordings were made at a resolution of 1920×1080 pixels with a frame rate of 30 fps. To stabilize the videos before performing the tracking, the point feature matching approach (from OpenCV library) was applied. A custom-developed image analysis program was employed to track pedestrian positions and velocities. To enhance accuracy and reduce noise, velocity calculations were performed using a sliding window of 0.8 seconds. A recorded trial illustrating the experiment is available in the Supplementary Movie 2.

Confined Random Motion in Japan

The experiment was conducted at the University of Tokyo, Japan, within a circular enclosure with a radius of 4 meters, delimited by chairs. A total of 39 participants (25 men and 14 women, aged 26.8 ± 7.4 years) were recruited through a website [31]. All participants provided informed consent, and the experimental protocol was approved by the ethical committee of the University of Tokyo.

Similar to the protocol implemented in Spain, participants were categorized as either LT or RT by asking them to perform a turn towards a wall prior to the experiments. An improvement introduced in this study was repeating this assessment two other times at different moments of the two-hour experiment: once during the first break and again at the conclusion. This allowed us to evaluate the consistency of turning direction among participants. A high level of consistency ($\sim 85\%$) was observed, with participants turning in the same direction in all three cases (see Supplementary Table II for details). The experimental conditions varied in terms of global density and the percentage of RT, as detailed in Table. I of the SI.

Each experimental trial lasted 45 seconds. Staff members first placed participants randomly throughout the enclosure to ensure a broad spatial distribution. Upon hearing a sound signal, they began walking randomly, as in the Spanish experiment. Another signal marked the end of the trial. To avoid transient effects, the first 5 seconds of each trial were excluded from the analysis. Each experimental condition was repeated four times, changing the participants included in the test whenever possible.

The experiments were recorded using a camera mounted 6 meters high in an azimuthal position above the centre of the room. The recordings had a resolution of 1920×1440 pixels and a frame rate of 30 fps. Videos were later analysed using PeTrack software [32, 33] to extract the coordinates of pedestrians based on their coloured caps. To facilitate identification, LT participants were given yellow hats, while RT participants were given red hats to wear during the experiments (discrimination was performed based on the turning direction in the initial test before the experiments). As in the Spanish experiments, velocities were calculated using a sliding window of 0.8 seconds. One example of the experiment is included in the Supplementary Movie 3.

Given that the experiment was conducted in Japan, where we hypothesized that lane formation predominantly occurs on the left side, it was essential to confirm whether this assumption held true. To validate this hypothesis, a questionnaire was administered to participants during the informative session for the experiments. The questionnaire presented participants with a series of images showing an individual walking in a corridor at varying distances (refer to the Supplementary Information for details). Participants were asked to indicate their preferred walking direction. The results of this survey (summarized in Table 2, SI) revealed a clear preference for walking on the left side (Section A, SI), confirming the hypothesis.

Nursery School in Japan

This experiment, conducted by Jun Ichikawa et al. [17], analysed the emergence of spontaneous social movement in children during eurhythmics activities in a nursery classroom setting. Specifically, the study examined a warm-up activity where children run freely around the room while the instructor plays the piano (see Fig. 1c).

Data were collected from four distinct class groups, each with a different mean age, all under six years. The individual positions of the children were included as Supplementary Information in the article. Velocities were calculated from these positions using a 0.8-second sliding window, as the videos were recorded at 20 fps. For each homeroom, several periods of motion were analysed, lasting between 5–10 seconds. These periods were interspersed with pauses when the instructor stopped playing. The number of periods per group varied (see Table I in SI), with at least two repetitions recorded for each class. For further details about the experimental setup and methodology, readers are referred to the original article [17].

Elicitation of Social Norms

For our elicitation of social norms we resorted to well established concepts and methods proposed by Bicchieri [24, 26]. Participants were students from the University of Navarra, approximately half of them Spanish and half from different foreign countries. They were shown the picture in Fig. 5(a) and went through the following questionnaire:

1. This is a ring with people inside. Picture yourself as if you were one of these persons, and you would like to walk in circles. In which sense would you move? (CW/CCW)
2. In which direction do you think most of the people will move? (CW/CCW)
3. In which direction do you believe that others expect you will move? (read twice) (CW/CCW)

Question (1) elicits the decision the person would take in the hypothetical case. Questions (2) and (3) elicit empirical and normative expectations, respectively.

Answers to the questionnaire were economically incentivized in order to obtain more careful responses. To that end, answers to questions (2) and (3) were compared to experiments and with answers to question (1) respectively; people answering questions (2) and (3) correctly (meaning either in agreement with the experiments for question (2) or with the majority of answers in question (1) for question (3)) entered a lottery for four gift cards of 25 euros each. We received a total of 168 valid responses.

Individual Motion

The last experiment, conducted at the University of Navarra, aimed to examine the influence of individual characteristics on the turning preference of pedestrians. A total of 209 participants (88 men, 121 women) were recruited over three days. Participants were university students and staff who volunteered to take part after being approached near the designated experimental area. All participants provided verbal consent. Since no personal information was collected and recordings were anonymized, with no faces captured, the University of Navarra's ethics committee told us that no further ethical approval was required.

The experiment was conducted within a hexagonal enclosure delimited by chairs and tables, with each side measuring approximately 4.6 meters (Fig. 8a). Prior to the experiment, all participants underwent a series of assessments to determine their hand, foot, and eye dominance (left or right preference). For those who were unaware of this information, various tests were conducted. Foot dominance was determined by instructing participants to kick a wooden object a couple of times; if they alternated between feet, they were subsequently asked to simulate stepping on an insect to identify a consistent preference. Eye dominance was evaluated using the Miles test [34]. Independently, to examine how restricted eye laterality affects movement patterns, 51 participants wore a patch over their right eye.

During the experimental trials, individuals were instructed to move freely within the enclosed space for 60 seconds without stopping. The experiments were recorded using a Go-pro camera mounted 5 meters above the centre of the arena, capturing footage at a resolution of 3840×3360 pixels and a frame rate of 25 fps. The videos were analysed using a custom-developed image analysis program to track the positions. As always, velocities of the participants were calculated using a sliding window of 0.8 seconds. The Supplementary Movie 4 includes a video recording of one experiment.

Metrics and Nomenclature

For all experiments, the rotation (both individual and collective) was quantified by means of the polarization parameter [18]. Given a pedestrian i at time t, the individual polarization value m_i is defined as:

$$m_i(t) = \hat{v}_i(t) \cdot \hat{e}_i^{\varphi}(t) \tag{1}$$

where $\hat{v}_i$ is the normalized velocity vector, and $\hat{e}_i^{\varphi}$ is the azimuthal position calculated as $\hat{e}_i^{\varphi} = R_{90^\circ}\,\hat{r}_i$. This represents a 90º CCW rotation of the normalized position vector of the pedestrian $\hat{r}_i$ relative to the centre of the arena. Thus, when $m_i = 1$, it indicates a perfect CCW circular motion, while $m_i = -1$ correlates with CW rotation.

Based on this, we can define the following magnitudes:

- $\overline{\mathbf{m_i}}$: Time average of the individual polarization per pedestrian over all the experiment duration.
- Collective polarization $\mathbf{M(t)}$, defined as:

$$M(t) = \frac{\sum_i^N m_i(t)}{N}$$

  where N is the total number of people in the arena.
- $\overline{\mathbf{M}}$: Time average of the collective polarization over all the experiment duration.

Supplementary information.

- Supplementary Notes.
- Questionnaries used in the elicitation of social norms (English and Japanse Versions).
- Supplementary Movies 1-4.

Acknowledgements. We thank L. Urrea and C. Martín-Gómez for their help with the experiments. We also thank D. Maza for useful discussions.

Declarations

Funding: I.E.H, A.G. and I.Z acknowledge support from the Spanish Ministry of Science and Innovation through the Grants No. PID2020114839GB-I00 and No. PID2023-146422NB-I00 funded by MCIN/AEI/10.13039/501100011033, FEDER, UE. C.F. acknowledges support from the JSPS KAKENHI Grant No. JP23K13521 and K.N. acknowledges support from the JST-Mirai Program Grant Number JPMJMI20D1. A.S. acknowledges support from grant PID2022-141802NB-I00 (BASIC) funded by MCIN/AEI/10.13039/501100011033 and by 'ERDFA way of making Europe', and also from grant MapCDPerNets—Programa Fundamentos de la Fundación BBVA 2022.
Conflict of interest: The authors declare no competing interests.
Ethics approval and consent to participate: In all experiments, informed consent was obtained from all participants and/or their legal guardians. The experimental protocols were approved by the corresponding institutional and/or licensing committees.
Data availability: The data that support the plots within this paper are available via Zenodo at XXX.
Author contribution I.E.H, A.G. and I.Z. designed the research. I.E.H, C.F., A.G. and I.Z. designed the experiments. I.E.H, C.F., Z.S., A.G. and I.Z. built the experimental setup and recorded the experiments. A.S. designed the social norm ellicitation section. I.E.H, Z.S., A.S., A.G. and I.Z analyzed the data. I.E.H. and I.Z. wrote the paper. All authors revised the results and commented on the manuscript.

References

[1] Kretz, T., Grünebohm, A., Kaufman, M., Mazur, F. & Schreckenberg, M. Experimental study of pedestrian counterflow in a corridor. *Journal of Statistical Mechanics: Theory and Experiment* **2006**, P10001 (2006).

[2] Feliciani, C. & Nishinari, K. Experimental analysis of collision avoidance behavior. *Physical Review E* **94**, 032304 (2016).

[3] Bacik, K. A., Bacik, B. S. & Rogers, T. Lane nucleation in complex active flows. *Science* **379**, 923–928 (2023).

[4] Moussaid, M. *et al.* Traffic instabilities in self-organized pedestrian crowds. *PLoS computational biology* **8**, e1002442 (2012).

[5] Kretz, T., Grünebohm, A. & Schreckenberg, M. Experimental study of pedestrian flow through a bottleneck. *Journal of Statistical Mechanics: Theory and Experiment* **2006**, P10014 (2006).

[6] Hoogendoorn, S. P. & Daamen, W. Pedestrian behavior at bottlenecks. *Transportation science* **39**, 147–159 (2005).

[7] Murakami, H., Feliciani, C., Nishiyama, Y. & Nishinari, K. Mutual anticipation can contribute to self-organization in human crowds. *Science Advances* **7**, eabe7758 (2021).

[8] Garcimartín, A. *et al.* Redefining the role of obstacles in pedestrian evacuation. *New Journal of Physics* **20**, 123025 (2018).

[9] Gu, F., Guiselin, B., Bain, N., Zuriguel, I. & Bartolo, D. Emergence of collective oscillations in massive human crowds. *Nature* **638**, 112–119 (2025).

[10] Helbing, D. & Johansson, A. *Pedestrian, Crowd and Evacuation Dynamics*, 6476–6495 (Springer New York, New York, NY, 2009).

[11] Zanlungo, F., Feliciani, C., Yücel, Z., Nishinari, K. & Kanda, T. Macroscopic and microscopic dynamics of a pedestrian cross-flow: Part i, experimental analysis. *Safety science* **158**, 105953 (2023).

[12] Bain, N. & Bartolo, D. Dynamic response and hydrodynamics of polarized crowds. *Science* **363**, 46–49 (2019).

[13] Helbing, D., Buzna, L., Johansson, A. & Werner, T. Self-organized pedestrian crowd dynamics: Experiments, simulations, and design solutions. *Transportation science* **39**, 1–24 (2005).

[14] Mohr, C., Landis, T., Bracha, H. & Brugger, P. Opposite turning behavior in right-handers and non-right-handers suggests a link between handedness and cerebral dopamine asymmetries. *Behavioral neuroscience* **117**, 1448 (2003).

[15] Silverberg, J. L., Bierbaum, M., Sethna, J. P. & Cohen, I. Collective motion of humans in mosh and circle pits at heavy metal concerts. *Physical Review Letters* **110**, 228701 (2013).

[16] Echeverría-Huarte, I., Nicolas, A., Hidalgo, R. C., Garcimartín, A. & Zuriguel, I. Spontaneous emergence of counterclockwise vortex motion in assemblies of pedestrians roaming within an enclosure. *Scientific reports* **12**, 2647 (2022).

[17] Ichikawa, J., Fujii, K., Nagai, T., Omori, T. & Oka, N. Quantitative analysis of spontaneous sociality in children's group behavior during nursery activity. *Plos one* **16**, e0246041 (2021).

[18] Bricard, A. *et al.* Emergent vortices in populations of colloidal rollers. *Nature communications* **6**, 7470 (2015).

[19] Feliciani, C. & Nishinari, K. Empirical analysis of the lane formation process in bidirectional pedestrian flow. *Physical Review E* **94**, 032304 (2016).

[20] Murakami, H., Feliciani, C. & Nishinari, K. Lévy walk process in self-organization of pedestrian crowds. *Journal of the Royal Society Interface* **16**, 20180939 (2019).

[21] Helbing, D. A mathematical model for the behavior of pedestrians. *Behavioral science* **36**, 298–310 (1991).

[22] Moussaïd, M. *Etude expérimentale et modélisation des déplacements collectifs de piétons.* Ph.D. thesis, Université de Toulouse III (2010).

[23] Turiel, E. *The Development of Social Knowledge: Morality and Convention* (Cambridge University Press, Cambridge, UK, 1983).

[24] Bicchieri, C. *Norms in the Wild: How to Diagnose, Measure, and Change Social Norms* (Oxford University Press, New York, 2017).

[25] Cialdini, R. B., Kallgren, C. A. & Reno, R. R. A focus theory of normative conduct: A theoretical refinement and reevaluation of the role of norms in human behavior. *Advances in Experimental Social Psychology* **24**, 201–234 (1991).

[26] Szekely, A. *et al.* Evidence from a long-term experiment that collective risk changes social norms and promotes cooperation. *Nature Communications* **12**, 5452 (2021).

[27] Ma, Y., Lee, E. W. M., Shi, M. & Yuen, R. K. K. Flow rate optimization and stepping synchronization in single-file pedestrian movement. *Nature Human Behaviour* **5**, 447–455 (2021).

[28] Tomaru, T., Nishiyama, Y., Feliciani, C. & Murakami, H. Robust spatial self-organization in crowds of asynchronous pedestrians. *Journal of The Royal Society Interface* **21**, 20240112 (2024).

[29] Zuriguel, I. *et al.* Contact forces and dynamics of pedestrians evacuating a room: The column effect. *Safety Science* **121**, 394–402 (2020).

[30] Yi, S., Li, H. & Wang, X. *Understanding pedestrian behaviors from stationary crowd groups*, 3488–3496 (2015).

[31] https://www.jikken-baito.com.

[32] Boltes, M., Seyfried, A., Steffen, B. & Schadschneider, A. *Automatic extraction of pedestrian trajectories from video recordings*, 43–54 (Springer, 2010).

[33] Boltes, M. & Seyfried, A. Collecting pedestrian trajectories. *Neurocomputing* **100**, 127–133 (2013).

[34] Miles, W. R. Ocular dominance demonstrated by unconscious sighting. *Journal of experimental psychology* **12**, 113 (1929).