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Walk the Line: The role of gender and culture on the movement patterns of pedestrians based on a multicultural study

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ABSTRACT

Experimental work has opened new avenues for studying crowd behavior under well-controlled conditions with desirable levels of measurement accuracy. However, unlike many other areas of behavioral science, little attention has been paid to how reproducible and transferable crowd phenomena are between different populations. As such, there is only limited knowledge about how universal and generalizable experimental observations on crowd behavior are. This research explores how gender and culture impact pedestrian dynamics in single-file movement, a topic previously studied in isolation through disjointed and varied experiments. Here, for the first time, and as an attempt to investigate external validity and generalizability across cultures, we conduct the same experiment in five different countries. Each experiment examines the effects of varying gender compositions on single-file pedestrian movement. We observed consistent effects of different gender compositions on pedestrian movement across countries, with no significant deviations in the fundamental diagrams, especially in the bounded regime. Although there was some variability in acceleration behavior across countries. Interaction levels, clustering behavior, and pedestrian spacing patterns remained consistent between different gender compositions and countries. These results suggest that, while the behavior of collective motion varies by culture and gender composition, most aspects of pedestrian movement exhibit universal traits. Understanding these variations and commonalities can allow for better infrastructure design and planning tailored to the population of interest.

1. Introduction

Understanding the patterns and dynamics of pedestrian movement in crowds is crucial for planning, modeling, and assessing the level of service and risk in pedestrian facilities. The complexity of crowd movement, resulting from the numerous degrees of freedom in pedestrian actions, makes these patterns difficult to analyze. An effective method for simplifying and precisely identifying these movement patterns involves examining pedestrian behavior in single-file scenarios, where individuals move in a straight line.

This approach reduces additional complexity elements and can offer foundational knowledge that is essential to understand pedestrian dynamics in more natural settings. In other words, although crowd dynamics are per se two-dimensional (or even three-dimensional in some cases), the one-dimensional nature and simplicity of pedestrian movement in a single-file configuration provide a distinctive perspective for analysis, similar to using a microscope to observe the internal structure of a crowd. This methodology is particularly instrumental in examining the effects of specific factors, such as age (Cao et al., 2018), gender (Paetzke et al., 2022) and culture (Chattaraj et al., 2009), on pedestrian dynamics, which remains underexplored, constituting a major knowledge gap in the field.

Studies in single-file pedestrian dynamics have been driven by a variety of practical and theoretical reasons. For example, Huang et al. (2018b) investigated the effect of the width of the aisle on pedestrian behavior in vehicle aisles, while Ma et al. (2020) analyzed how height restrictions impact pedestrian flow in emergency situations. On the theoretical side, Ye et al. (2021) investigated how different motivations influence pedestrian movement on stairs, and Cordes et al. (2023)

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provided an overview of the application of agent-following models to numerically investigate the dynamics of single-file pedestrians. These investigations have collectively contributed to our foundational understanding of pedestrian movement, with direct implications for safety design and emergency preparedness.

A recent meta-study conducted by Xue and Shiwakoti (2023) on pedestrian walking in a single-file configuration revealed a mix of similarities and discrepancies between different research studies, highlighting the need for additional empirical investigations into various aspects such as geometric limitations (Ma et al., 2020), stairs and motivation (Ye et al., 2021), as well as the impact of rhythmic cues on movement (Yanagisawa et al., 2012; Li et al., 2023). Research focusing on age-related variances (Cao et al., 2018; Ren et al., 2019) has, for example, shown that older pedestrians demonstrate an increased sensitivity to spatial gaps when adjusting their speed.

Recent studies have focused on the impact of gender on pedestrian dynamics. Dias et al. (2022) identified disparities in acceleration and deceleration patterns during single-file movements, noting that males show more variability compared to females. His study was conducted in Palestine. In this paper, we use data from various countries, including Palestine, Japan, China, Germany, and Australia, to provide a broader perspective on these movement patterns.

In contrast, Paetzke et al. (2023) observed slight gender differences in speed at higher crowd densities and explored how the gender mix affects the speed-density correlation. Their results suggest that this correlation changes according to the gender makeup of the group, highlighting that homogeneous gender groups exhibit higher speeds at specific densities. However, de Schot et al. (2023) did not find a significant gender influence on walking behavior in virtual reality settings, suggesting potential avenues for further exploration in this area. Subaih and Tordeux (2024) found that the fundamental diagrams (that is, the speed-density relationship) for single-gender groups (either male or female) were similar. However, the fundamental diagram for mixed gender groups (both male and female) indicated a relatively slower speed compared to the diagrams for homogeneous groups.

Zibrek et al. (2020) examined personal space preferences in Virtual Reality (VR), finding that although gender did not significantly affect proximity, female observers preferred larger personal space distances than male observers.

In another study, Wang et al. (2021) investigated how gender and age affect walking characteristics, such as step length and step frequency. Their study did not reveal a notable variance in the relationship between progress and speed between genders within identical age groups. However, the analysis showed that the differences in step length and lateral movement were statistically significant between males and females between all age categories. For elementary school-aged children, gender significantly influenced step frequency. However, for middle-school children, the impact of gender on step frequency remained ambiguous (Wang et al., 2021).

Despite these findings, we believe that the influence of gender on walking patterns is not conclusively demonstrated, suggesting that the observed results may be sensitive to the choice of analytical methods, as indicated in Paetzke et al. (2023). Taken together, these studies indicate that the gender effect on pedestrian dynamics is most pronounced in particular density ranges and is shaped by the group's composition. The findings suggest a nuanced role for gender in pedestrian behavior, suggesting the need for more in-depth research to fully understand these patterns.

The influence of culture in single-file experiments was investigated by Chattaraj et al. (2009), who studied the differences between Indian and German participants, showing that the fundamental diagram in the Indian setup features higher speed values compared to the German data. Unfortunately, both experiments did not take the gender factor into account, so it is not possible to draw any conclusions about the gender factor between cultures. In another study, Bilintoh et al. (2023) compared the single-file dynamics of the experiments with German participants, Ghanaian participants, and African students in China.[1] The study found that Ghanaians required a smaller personal space zone, allowing them to travel more quickly than German pedestrians and African students in China at similar densities.

Both studies (Chattaraj et al., 2009; Bilintoh et al., 2023) presented experiments in which the gender composition of the participants was not a central focus. Therefore, our study aims to address this gap by systematically examining the combined role of culture and gender in the dynamics of single-file movement.

Modeling single-file movement: The above-mentioned experimental investigations have informed and inspired microscopic agent-based modeling of pedestrian dynamics, although not all aspects are clear, leading to the emergence of new modeling concepts that aim to better understand the movement of a single file. Cordes et al. (2023) provides an overview that presents numerous models exploring characteristics of single-file movement, such as stop-and-go waves and phase separation. The authors also present a comprehensive classification of these models and discuss their stability properties and limitations.

Single-file experiments can serve as a reference for assessing the validity of numerical models. Their accuracy can be evaluated by analyzing how well they reproduce key movement characteristics, such as step frequency, fundamental diagrams, acceleration/deceleration behavior, and headway-time.

Portz and Seyfried (2010), Kuang et al. (2012) introduced novel models to study the emergence of stop-and-go waves in single-file movement. Huang et al. (2018a) developed a biped model in one-dimensional space to investigate the lockstep phenomenon and stop-and-go waves. Most recently, Subaih et al. (2022) proposed a new approach based on artificial neural networks to approximate the fitting function that describes pedestrian movement without introducing modeling bias. Their results highlight the anisotropic character of the distance dependence on the neighbors on both sides.

Concluding note: While single-file movement may seem straightforward due to its one-dimensional setting, the literature reveals complex dynamics that have led to various empirical and theoretical conclusions. It is crucial to note, as highlighted in Haghani (2021), that the validity of experiments is paramount. The experiments described in the above literature overview were carried out a single time, thus lacking repetition and somewhat limiting the applicability of their findings and their use for robust validation of models. In addition, the geometrical setup was not consistent among all studies, making a direct comparison often arguable. In investigating pedestrian behavior through numerical simulations, the frequency of repeated simulations plays a critical role, as emphasized by Smedberg et al. (2021) and Feitelson (2015). The capacity to reproduce experiments for the purpose of confirming or questioning hypotheses and existing findings is of the most importance and remains a limiting factor.

Our study seeks to remedy this reproducibility deficit by replicating identical experiments in five different countries, with the goal of obtaining statistically sound conclusions regarding the influence of culture and gender on pedestrian behavior.

2. Description of experiments

In this study, we conducted a series of experiments to explore the dynamics of pedestrian movement within single-file configurations in five different countries: Australia, China, Germany, Japan, and Palestine. These experiments were designed to maintain similar conditions in all test environments, thus ensuring the reliability and comparability of our findings. The data collected from these experiments provide

[1] Although both groups consist of African participants, the first experiment involved students living in Ghana, while the second experiment involved African participants living in China.

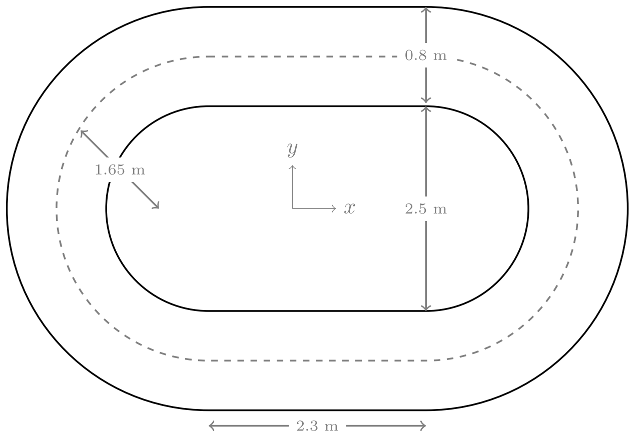


Fig. 1. Geometry and dimensions of the experimental setup. In all experiments, two tracks were used simultaneously and a high wall was used to separate both tracks so that people could not see on the other side. Start and stop signals were given using loud announcements so that both tracks could hear them. In the figure, the dotted line is used to indicate the center-line of the course and the tick line in the middle represents the wall. It is important to note that although geometry was the same for all countries, materials and method used to limit the course were slightly different as visually shown in Fig. 2.

valuable insights into pedestrian dynamics and spatial behavior. Importantly, all experimental trajectories are made available as open-access data, along with an open-source interactive application designed for detailed data exploration. See "Data availability" for more details.One of the main factors we focused on in our research was the gender makeup of the pedestrian groups, which we deliberately divided into four groups: exclusively male, exclusively female, randomly mixed and alternately mixed. The alternately mixed group involved alternating men and women to investigate how organized gender diversity affects movement patterns. However, the randomly mixed group included men and women in no particular order. The reason for this configuration is to investigate the potential impact of gender on the dynamics and to determine if such an influence can be accentuated by the structured arrangement.

The experimental setup replicated an oval-shaped geometry with closed boundary conditions, allowing us to closely observe how the participants navigated this constrained space. See Fig. 1 for details and dimensions of the setup. This setup provided a controlled environment to explore aspects of single-file movement influenced by gender composition and spatial constraints.

Although the geometry of our experiments is simple and the general concept should be already clear to the readers, the microscopic dimension of our investigation makes small, apparently irrelevant, details rather important, especially regarding the interpretation of the results. For example, some experiments were performed indoors while others were performed outdoors. For most experiments involving crowds or collective motion, such a detail is not really relevant. However, here we wish to specifically compare microscopic characteristics of single-file motion between gender and culture, and those details can *potentially* be relevant. As a foreword, before digging into the specifics of each experiment, we note that all experiments were performed during the COVID-19 pandemics. This is important to note because conducting perfectly similar experiments across three continents is challenging under normal conditions, and the varying levels of restrictions during the pandemic made this task even more difficult. Due to the special circumstances occurring when experiments were performed, their location, recruiting method, maximum number of participants, etc. were directly or indirectly affected by the health regulations of each university/country. Consequently, the details presented below should be considered with these organizational limitations in mind.

Table 1 presents details relative to each experiment. The table is organized into categories presenting differences among several environmental factors, such as location, time of the day or more technical aspects, including for example, camera resolution or shooting location.

All experiments were performed in university campuses and generally lasted a few hours. However, experiments in Australia, Germany, and Palestine were performed indoor, while those in China and Japan were performed outdoor. Since weather was favorable for those experiments we can exclude large bias, although temperature can play a role on individual speed, as people usually walk faster in colder environments (Weidmann, 1992). In most countries, 80 people or more were recruited (less in Palestine), with a balanced ratio between genders. In the experiments performed in China and Palestine, only university students were recruited, making the average age of participants rather low. In Australia, recruitment was carried out among the public resulting in some participants being in their 50 s or 60 s.[2] In Japan, due to problems in recruiting 80 students, help was sought from an organization promoting social activities among retirees. As a consequence, both average age and deviation are higher than other countries. In the Japanese experiments (and only there) free walking speed was measured individually, showing a significant difference between students and the elderly (details for the influence of the elderly are given in Appendix B). However, students and elderly were always present in the same proportion in all experiments, therefore, although we cannot exclude some bias related to age composition in Japan, this bias is likely to be small, especially in light of the comparative analysis performed here. Design and procedures of all experiments were reviewed by the corresponding ethical commissions and permission was obtained before collecting data (i.e., before performing the experiments). In all countries, only adult individuals having no walking impairment and generally healthy were allowed to take part in the experiments. In addition, depending on the COVID-19 situation, in some countries restrictions applied on non-infected individuals (for example, in Germany tests were done on-site). All experiments were recorded using video cameras at high resolution and trajectories were extracted using PeTrack software (Boltes and Seyfried, 2013). However, differences exist for orientation of the camera and types of data collected. In Australia, Germany, and Japan cameras were positioned directly over the course resulting in an overhead shooting (see also Fig. 2). In the Chinese experiments, the camera was also set at a considerable height (11 m), yet not overhead, resulting in a partially sideways shooting. However, PeTrack software used for tracking takes into account perspective, so extracted trajectories should be comparable for all experiments. This is however not the case for the Palestinians experiments, in which the camera was located next to the course, along the straight section, recording people sideways. In short, people would appear from the left of the camera, move along the straight section and disappear from the right side. For these reasons, trajectories obtained from Palestinians experiments are not complete (i.e., people are not tracked the whole time over the full length of the course) limiting analytical approaches on these data. In addition, the maximal number of Palestinians was only 30 participants per run, which yields lower densities compared to other countries (40). Finally, it may be worth remarking that Japanese experiments were the only ones in which two different cameras (same model, same settings) were used for each course. This is likely an irrelevant aspect, yet it is worth remarking this minor difference to highlight the importance of details in this work.

The density (number of people per meter length of the course) was changed by increasing the overall number of people. The experiments started with 4 people, and the number gradually increased to a maximum of 40. However, there are differences between countries regarding the number of density steps tested. For instance, in the

[2] Age is not available for the participants in Australia's experiments and this statement is based on information from the organizers.

Table 1
Details for the experiments performed in the cultural areas considered in this study.

Category	Information	Australia	China	Germany	Japan	Palestine
General info	Date	06/10/2022	12/11/2022	11/10/2021	10/12/2022	2018 (date N/A)
	Time	13:00-14:30	14:00-17:00	10:00-13:30	13:00-15:30	N/A
	Facility	John Niland Gallery Scientia Building	Xipu campus, Southwest Jiaotong University	Mitsubishi Electric Halle, Düsseldorf	RCAST campus, The University of Tokyo	Arab American University
	Location	Indoor	Outdoor	Indoor	Outdoor	Indoor
	Temperature	≈20 °C	≈10 °C	N/A	≈15 °C	≈29 °C
	Weather	N/A (indoor)	Cloudy	N/A (indoor)	Sunny	N/A (indoor)
Participants	Total number	80	109	80	80	47
	Age	N/A	20.1 ± 2.1 yr	27.2 ± 7.0 yr	47.4 ± 24.2 yr	20.5 y ± 2.5 yr
	Height	N/A	169.7 ± 8.6 cm	175.7 ± 9.8 cm	163.7 ± 8.2 cm	168 ± 16 cm
	Gender (females/males)	40/40	56/53	40/40	40/40	26/21
Ethics and related	Recruitment method	Fliers, university e-mail lists, etc.	Online recruitment through university	SNS, e-mail lists, etc.	SNS (Twitter, etc.)	Fliers, university e-mail lists, etc.
	Selection criteria	Adults healthy individuals without walking impairments				
	Remuneration	110 AUD	70 RMB	N/A	4200 yen	Credit points
	Ethical screening	UNSW Human Research Ethics Committee	Ethical Committee of Chengdu General Hospital	German Psychological Society	Ethical Committee of The University of Tokyo	Arab American University
	COVID-19 restrictions?	Lifted at the time	Yes, few for outdoor	Yes, tests on-site	Yes, few for outdoor	None (2018)
Technical details	Camera model	N/A	GoPro 5 Black	Marshall CV365-CGB	GoPro Hero+	Nikon D610 and Nikon D3300
	Resolution	1920 × 1080	1920 × 1080	1920 × 1080	1920 × 1080	1280 × 720
	Frame rate	25 fps	30 fps	50 fps	30 fps	25 fps
	Shooting position	Overhead	Sideways	Overhead	Overhead	Sideways
	Shooting height	≈ 9 m	≈ 11 m	≈ 9 m	≈ 6 m	N/A
	Tracking software	PeTrack				

Table 2
Summary of experiment runs by country and gender composition. "Mixed Sorted" refers to runs with alternating men and women, whereas "Mixed Random" refers to runs with men and women in no particular order. The direction of movement is clockwise (CW) or counter-clockwise (CCW).

Country	Direction	Female	Male	Mixed sorted	Mixed random
Australia	CW	6	6	2	2
China	CCW	23	22	14	15
Germany	CCW	9	10	24	24
Japan	CW	15	15	0	18
Palestine	CCW	6	6	12	0

Chinese experiments, density was increased by adding 4 people at a time (i.e., 10 steps in total). However, Australian experiments had only 4 steps. Regardless of this, all countries are in the same low- (4 people) and high-density (40 people) condition, thus allowing a valid comparison at both extremes. In all countries, the trials lasted about two minutes, although the duration was not strictly imposed. As a general rule, a single trial would be judged "complete" (in terms of the amount of data collected) when each participant turned at least one time around the course. The case with 40 people (the maximum density) could be seen as an exception here, since in some countries people barely moved in such conditions. In Table 2 we summarize the distribution and classification of the experimental conditions performed in each country. China has the highest number of runs (74), followed by Germany (67), Japan (48), Palestine (24), and Australia (16). It is also worth noting that in Japan and Palestine, mixed random or mixed sorted (both were not performed), making it not possible to compare all counties in terms of order and gender influence. However, all countries have at least six runs for each gender, making a comparison of the uniform composition possible and reliable. Fig. 2 provides a qualitative comparison among all experiments and should visually complement the details provided in Table 1. As can be seen, the experimental setup is the same in each country, although some minor details are different. For example, in China and Japan the course is fully marked, whereas a line is used only in the straight section in Germany and Palestine, and small cones are used in Australia. Again, this is very likely to play an insignificant role in the results, but highlights the challenges in performing the *very same* experiment through various cultural and geographical contexts. The frames shown in Fig. 2 should also clearly illustrate the methods used to extract trajectories. In all experiments, cap color or QR codes (or a combination of them) were used to track the participants and obtain the trajectories. In Fig. 3, a set of pedestrian trajectories from various experimental trials in mixed-gender groups is displayed, depicting scenarios from less crowded to very congested settings. Trajectories are color-coded according to the gender of the individuals.

3. Results

In this section, we present the results considering different aspects of the experiments. First, in Section 3.1 we investigate the connection between density and speed, using the fundamental diagram concept (Vanumu et al., 2017). Next in Section 3.2 we investigate the acceleration and deceleration behavior of pedestrians. Furthermore, we conduct an in-depth proximity analysis using various methods to carefully examine how pedestrians are spatially distributed across the countries and gender groups under investigation. In Appendix C, we start by investigating how the distances between pedestrians change in response to variations in density. Using the pair-distribution function, we further investigate in Section 3.3 the structural composition of the crowd. This methodological approach allows us to quantitatively assess the spatial arrangement of pedestrians and identify clustering or dispersion patterns within the crowd.

Finally, in Appendix D we examine the probability distributions of various distances, with a particular emphasis on differentiating between types of neighboring pedestrians.

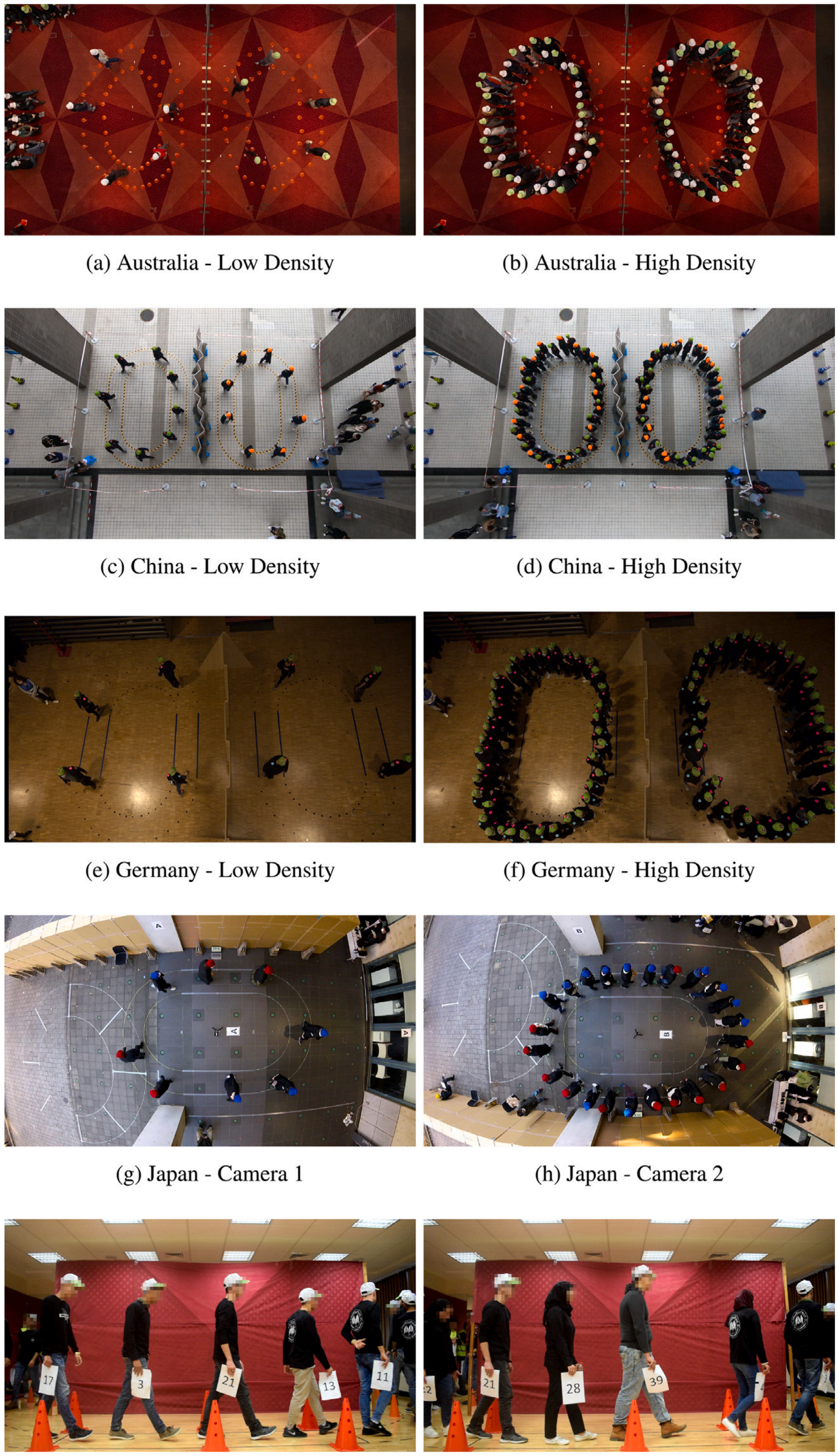
3.1. Fundamental diagram

In the following section, we measure pedestrian density and speed within a rectangular domain defined by Cartesian coordinates. This region is defined as $\mathcal{X} \in [-1.4\,\mathrm{m}, 1.4\,\mathrm{m}]$ and $\mathcal{Y} \in [-2\,\mathrm{m}, -1\,\mathrm{m}]$. For an individual pedestrian i within this region, we define the local pedestrian density, $\rho_i = 1/h_i$, where h_i represents the average half-distance to the nearest neighbors in the immediate vicinity of the pedestrian. Specifically, h_i is calculated as

$$h_i = \frac{1}{2}\left(\mathrm{dist}_{\mathrm{prev}} + \mathrm{dist}_{\mathrm{next}}\right), \tag{1}$$

which is the arithmetic mean of the distances to the preceding ($\mathrm{dist}_{\mathrm{prev}}$) and subsequent ($\mathrm{dist}_{\mathrm{next}}$) pedestrians along the direction of movement. The speed of a pedestrian, denoted s, is determined by examination of the motion during a defined time period Δt, and by computing the Euclidean distance covered within that time period.

In analyzing the fundamental diagrams derived from pedestrian flow experiments conducted in five different cultural contexts (Australia, China, Germany, Japan, and Palestine), a characteristic trend emerges, consistently illustrating a decrease in pedestrian speed with an increase in density. This phenomenon reaffirms the well-documented nature of the fundamental diagram in capturing the dynamics of pedestrian movement under varying densities. Despite the diverse cultural backgrounds of the participating groups, no clear deviations were observed in the resulting fundamental diagrams. The exception is the Palestinian data, which lacks representation at high densities due to



(a) Australia - Low Density (b) Australia - High Density

(c) China - Low Density (d) China - High Density

(e) Germany - Low Density (f) Germany - High Density

(g) Japan - Camera 1 (h) Japan - Camera 2

(i) Palestine - Males Only (j) Palestine - Mixed Gender

Fig. 2. Sample frames from different experiments in various countries. For Australia, China, Germany, and Japan, examples are taken at low and high densities. In Palestine, a frame with males only is compared with one including both genders. In the case of Japan, each frame is from a different camera relative to a different course.

fewer runs with a large number of participants, unlike the data from other countries.

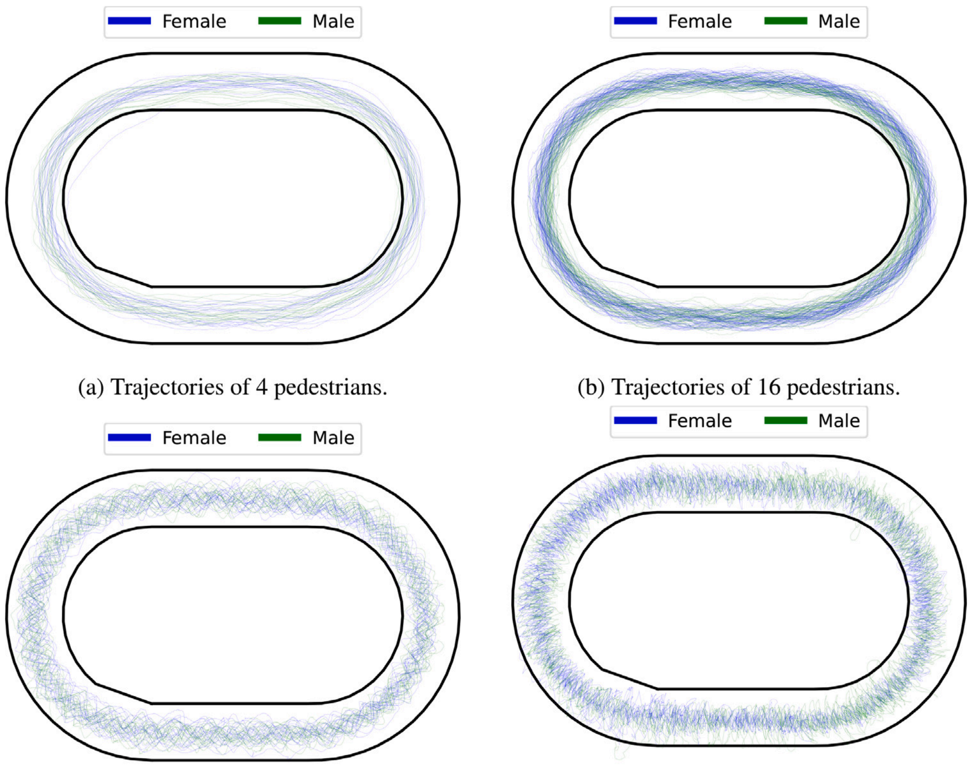
In the Palestinian run, which involved mixed gender participants and high-density conditions, people were reluctant to move, seemingly to avoid physical contact with the opposite gender. In contrast, this behavior was not observed in other countries, where the hesitation to move was more likely caused by physical constraints than gender-related considerations.

All data were fitted using Eq. (2) (Weidmann, 1992):

$$s = s_0 \cdot \left[1 - \exp\left(\gamma \cdot \left(\frac{1}{\rho} - \frac{1}{\rho_m}\right)\right)\right], \tag{2}$$

with γ a calibration constant, s_0 the free flow speed and ρ_m the maximal density. See Table 3 for summary of the parameter values.

The uniformity is visually illustrated in Fig. 4, where, except for the Palestinian data, all data points converge regardless of the cultural



(a) Trajectories of 4 pedestrians.

(b) Trajectories of 16 pedestrians.

(c) Trajectories of 24 pedestrians.

(d) Trajectories of 40 pedestrians.

Fig. 3. Trajectories of different runs with different numbers of pedestrians (German experiments). Colors are correlated to gender (blue female, green male). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Parameter values for the Weidmann fundamental diagrams per country. See Eq. (2).

Country	s_0 [m/s]	γ [1/m^2]	ρ_m [1/m^2]
Australia	1.39	0.76	3.36
China	2.04	0.43	3.52
Japan	1.22	0.99	2.66
Germany	1.21	1.06	3.19
Palestine	1.74	1.13	2.21

or gender characteristics of the participants, indicating a significant overlap. Our findings suggest that pedestrian behavior, as captured in the macroscopic observations of this study, adheres to a set of universal principles that appear to be minimally influenced by cultural or gender differences.

Note that the differences registered in the Palestinian data are probably due to the lack of a high-density regime, unlike the other experiments.

These results underscore the robustness of the fundamental diagram as a tool for validating models of pedestrian dynamics, reinforcing its applicability in the design and evaluation of public spaces and pedestrian facilities around the world. The observation of a universal behavioral pattern, as initially observed in Zhang et al. (2014), not only simplifies the task of urban planners and designers but also provides a solid foundation for the development of more generalized theories of pedestrian dynamics.

To evaluate the variation and similarity in the fundamental diagrams Fig. 4, a statistical analysis is performed on the speed distributions divided by specific densities. More precisely, the Kolmogorov–Smirnov (KS) distance (Kurtc et al., 2019) is calculated to measure the differences between the sets of cumulative distribution functions observed for pedestrian speeds under different density scenarios.

Fig. 5 shows a combined presentation of KS values for the female-only and male-only compositions in all countries in the bounded regime ($\rho \in [1.0\,\mathrm{m}^{-1}, 2.5\,\mathrm{m}^{-1}]$). We observe a symmetrical structure, confirming the above-observed universality in the fundamental diagrams across countries. For the definitions of the KS metric, refer to Appendix A, where we present the KS distances in relation to density between different countries.

3.2. Acceleration and deceleration behavior

Acceleration and deceleration, collectively called acceleration, illustrate how pedestrians react to potential collisions with their surroundings. So far, both the significant (Dias et al., 2022) and the insignificant (Paetzke et al., 2023) influence of gender differences have been reported, and the influence of culture is still unclear. Here, a comprehensive comparison of acceleration over gender and culture will be performed. The acceleration information includes two aspects: the acceleration value indicating how much pedestrians react to potential collisions and the timing of acceleration indicating when pedestrians begin to respond to the potential collisions.

On the one hand, the acceleration value a is calculated from the velocity difference of the same person. The variation in the absolute value of acceleration $|a|$ between genders and cultures is depicted in Fig. 6. Generally, a decreases with increasing number of pedestrians N. This is because a larger N corresponds to a lower velocity and a decrease in velocity with N allows smaller ranges for change in velocity. Still, we can find differences between genders and cultures.

For Australia, China and Germany in Fig. 6(a), Fig. 6(b), Fig. 6(c), cases involving only males have a higher a than cases involving only females, indicating that males accelerate more than females. In addition, mixed random and mixed-sorted cases have numerous medium a values between male and female cases. This suggests that in experiments in Australia, China, and Germany, males tended to react more than

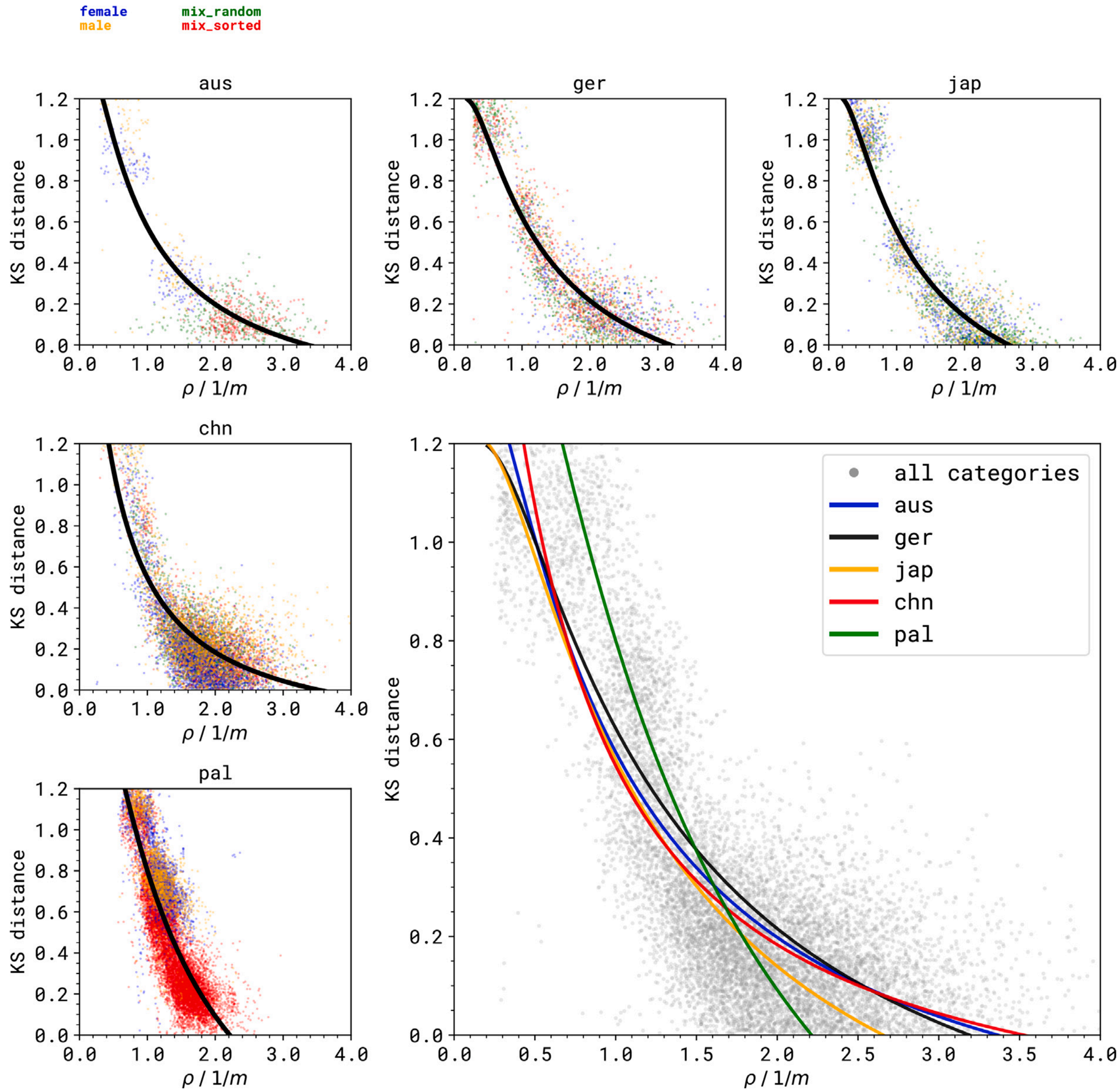


Fig. 4. Fundamental diagrams representing the characteristics of pedestrian flow for various countries and a combined diagram for comparison. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

females, and mixed cases behaved between males and females. In contrast, for Japan and Palestine in Fig. 6(d), Fig. 6(e), the influence of gender on a is not significant. This suggests that for Japan and Palestine, the differences between males and females in acceleration were not as large as for the others.

The insignificance of the gender influence in Japan and Palestine can be related to their insignificant difference in the acceleration of the free flow. As evidence, we took $|a|$ of individual free-flow walking pedestrians from experiments in Japan, where pedestrians were required to walk the course in Fig. 1 without allowing them to see others' walking (i.e., they were asked to walk the course one by one independently). To obtain the free-flow acceleration, we arbitrarily take the acceleration of pedestrians' start process, i.e., the walking process between when the speed reaches 0.1 times to when it reaches 0.9 times its (final) free-walking speed. A comparison of the values of a in males and females is shown in Fig. 7, showing that the free flow a of females and males is not significantly different. This is consistent with the insignificant difference in gender in crowd experiments shown in Fig. 6(d). Please note that although elderly and young students were recruited in the experiments, the influence of age rarely affected our results with detailed explanations seen in Appendix B.

However, there is a time delay that indicates how prompt pedestrians react to their surroundings. Specifically, a pedestrian usually decides to accelerate when he/she has a different speed than the former pedestrian, and this time lag τ is the duration from when he/she is influenced by the speed difference to when he/she begins to accelerate. The value of τ is derived from the correlation between $s_{i+1}(t)-s_i(t)$ and $a(t+\tau)$, with $s_{i+1}(t)$ indicating the speed of the former pedestrian $i+1$, $s_i(t)$ indicating the speed of the subsequent pedestrian i, and $a(t+\tau)$ the acceleration of the pedestrian i at time $t+\tau$ (Dias et al., 2022). The value τ that corresponds to the strongest correlation between $s_{i+1}(t)-s_i(t)$ and $a(t+\tau)$ is considered the optimal time delay τ. Fig. 8 gives examples corresponding to the optimal τ with the strongest correlation between $s_{i+1}(t)-s_i(t)$ and $a(t+\tau)$.

Previous studies on the influences of gender and culture on τ show different results. In particular, τ was found to be only significant in density other than gender and culture (Xue et al., 2023) with German students of the 5th and 11th grade (11–12 and 17–18 years, respectively) as participants, while significant in gender in Dias et al. (2022)

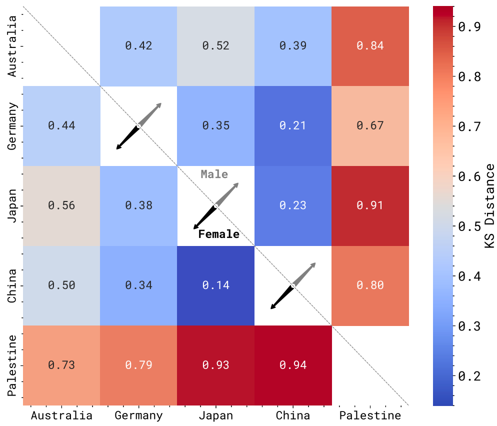


Fig. 5. Combined KS Distance Heatmap for Male and Female Populations. The heatmap displays the Kolmogorov–Smirnov (KS) distances between various populations at mid-densities. The upper triangle shows the KS distances for male populations, while the lower triangle shows the KS distances for female populations. The populations compared are from Australia, Germany, Japan, China, and Palestine. The color intensity indicates the magnitude of the KS distance, with values annotated for clarity. The observed symmetry suggests identical distances between genders, which could imply gender-independent distribution differences. Note that this representation is based on Fig. 13, hence KS distances among gender for the same country are not considered. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

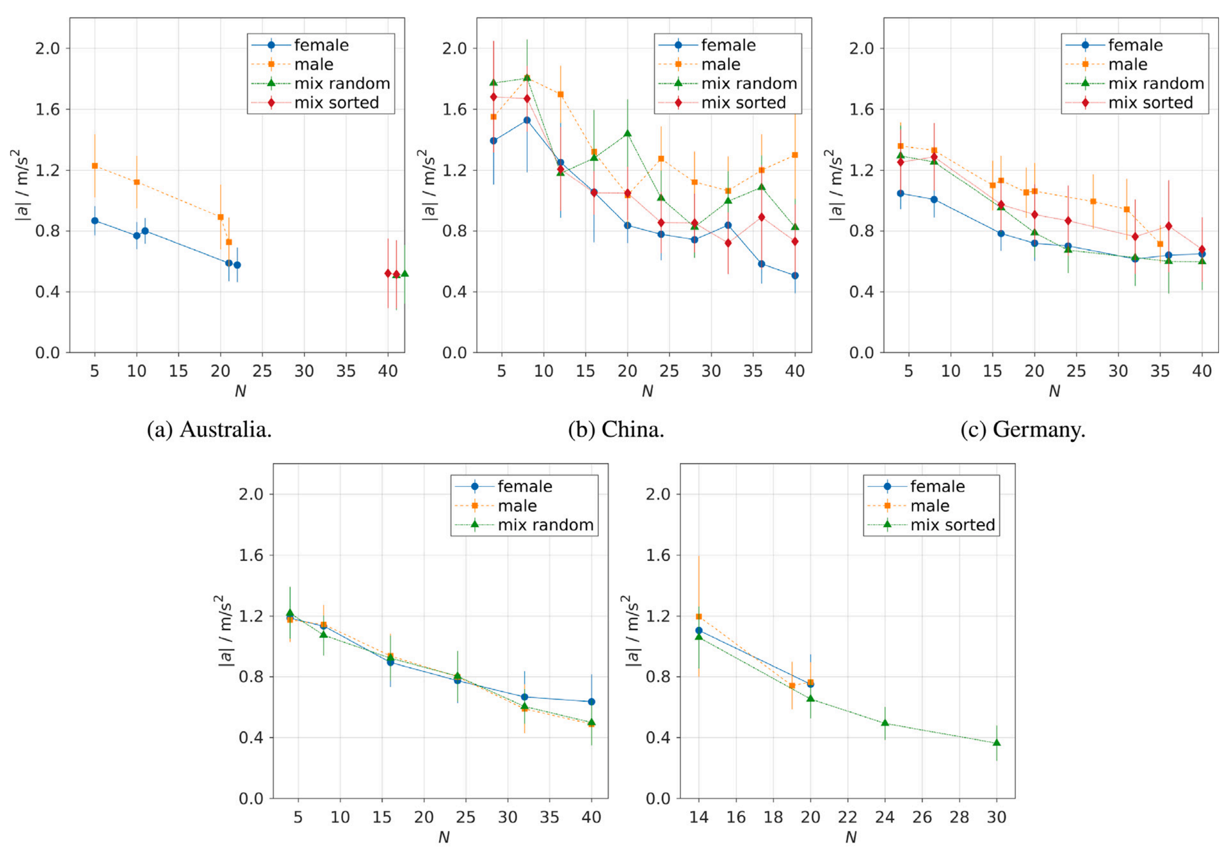
with members of Palestinian universities (ages not reported). This difference is possibly due to the demographics of different participants. Therefore, τ in our experiments is used to thoroughly examine the influence of gender and culture.

The variation of τ on culture and gender can be seen in Fig. 9. Concerning culture influence, variations of τ in Australia, China, Germany and Japan show similar trends. When $N \leq 20$, τ shows a decreasing trend. This indicates τ when $N \leq 20$ is mainly affected by density, which is natural because a more crowded situation can force pedestrians to respond earlier to avoid collisions. When $N > 20$, τ fluctuates around 0.3 s in most cases, which can be regarded as the general response capacity to potential pedestrian collisions in our experiments. In contrast, in Palestine, the decreasing trend is not valid for female-only cases. We believe that this is caused by the incomplete trajectory data in Palestine, which means that Palestine's experiment has much fewer samples than the other countries, making the τ values more scattered with wider error bars. Therefore, we consider that the difference in Palestine is mainly due to its collection of data other than the culture. Concerning the influence of gender, no general differences between genders between cultures can be observed. This means that τ is only related to the density of pedestrians, while not significantly affected by gender, which is consistent with the results of Xue et al. (2023).

In summary, our acceleration results indicate that culture and gender significantly influence the value of acceleration but have an insignificant effect on the timing of acceleration. This suggests that while the abruptness with which pedestrians handle potential collisions varies between genders and cultures, the timing of when they begin to respond to potential collisions remains relatively consistent.

3.3. Self-organized structure in experiments

The pair distribution function, $g(r)$, is a common tool in materials science that is used to infer the atomic or molecular structure of materials. $g(r)$ serves as a metric, providing insight into the probability



(a) Australia. (b) China. (c) Germany.

(d) Japan. (e) Palestine.

Fig. 6. Acceleration variations across all countries.

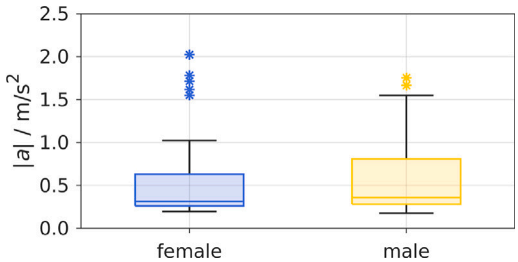


Fig. 7. Comparison of Japan free-flow acceleration between males and females, which is insignificant with $p = 0.65 > 0.05$ using t-test.

density function of observing two pedestrians separated by a distance r ($P(r)$), normalized by an analogous probability in a non-interacting pedestrian ($P_{ni}(r)$) scenario (Karamouzas et al., 2014):

$$g(r) = \frac{P(r)}{P_{ni}(r)}. \tag{3}$$

In general, a value of $g(r) > 1$ indicates that the distance r is frequently observed between two pedestrians, while a value $g(r) < 1$ might avoidance or dispersion at that range.

As the value of $P_{ni}(r)$ is not known, we replicate the data set multiple times to enhance the sample size, then thoroughly shuffle the merged data randomly. This process disrupts any preexisting spatial patterns and interactions between pedestrians, essentially generating a randomized scenario that mimics the conditions of pedestrians not interacting with each other, allowing for the estimation of $P_{ni}(r)$.

To estimate the distribution, we used strict binning with bins of size 0.1 m. Fig. 10 shows a sample for a pair distribution function with Australian data.

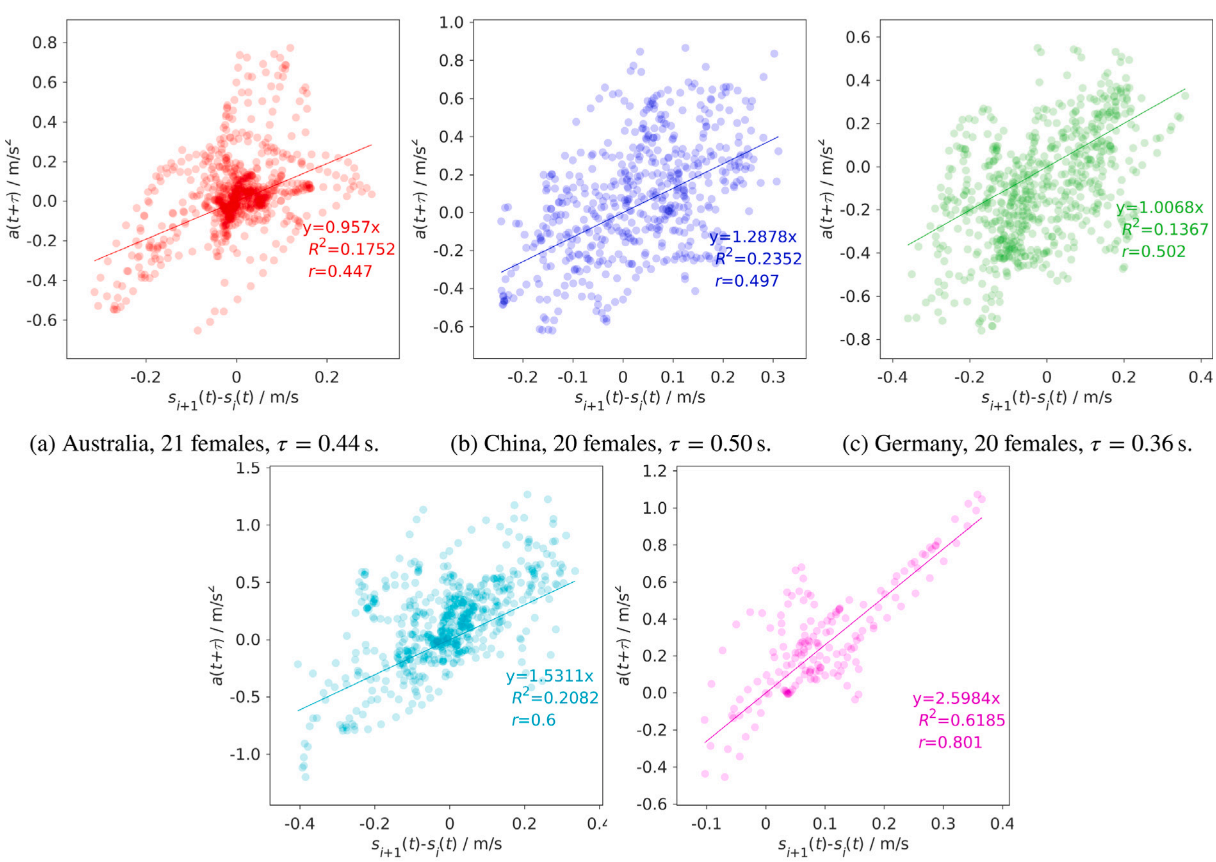
In the following, and in order to quantify eventual differences between the different categories and countries, we will be focusing on the following quantities: the position of the first peak and its distance to the second peak. These metrics potentially serve as indicators of culturally influenced preferences in personal space and group dynamics. By comparing these parameters across different demographic categories and countries, our aim is to describe the influence of cultural factors and gender on the spatial distribution of pedestrians.

The analysis categorizes pedestrians into four distinct categories: female versus male and mixed sorted versus mixed random.

Pair-distribution metrics. This study concentrates on the position of the initial peak and its proximity to the subsequent peak at moderate densities, specifically for runs involving 20 pedestrians. However, the Japanese data set lacks data for 20 pedestrians, instead providing information for 16 and 24 pedestrians. To enhance comparability, we will fit the Japanese pair-distribution metrics while varying the number of pedestrians shown in Fig. 11.

Gender-specific findings. Fig. 12(a) illustrates the correlation between the initial peak position and the distance to the second peak for medium densities in five countries, revealing distinct gender-based patterns.

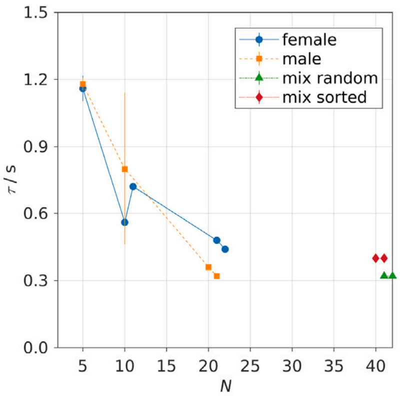
Australia and China exhibit contrasting gender dynamics. In Australia, both genders share an initial peak at 0.7 m, but females show a tighter secondary grouping (0.5 m) compared to males (0.7 m). Conversely, Chinese pedestrians of both genders initially cluster at 0.8 m,



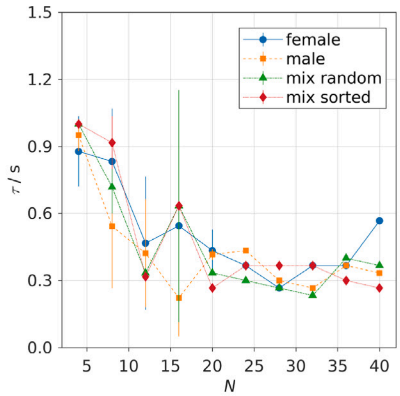
(a) Australia, 21 females, $\tau = 0.44$ s. (b) China, 20 females, $\tau = 0.50$ s. (c) Germany, 20 females, $\tau = 0.36$ s.

(d) Japan, 24 females, $\tau = 0.40$ s. (e) Palestine, 20 females, $\tau = 0.36$ s.

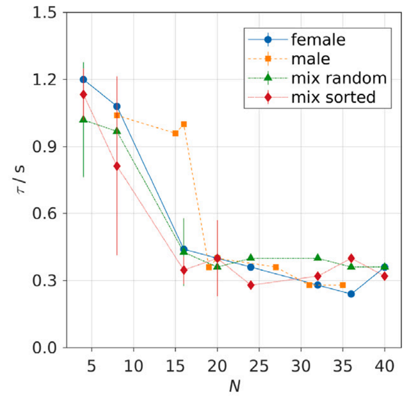
Fig. 8. Illustration of the existence of time lag. r is the Pearson's correlation coefficient.



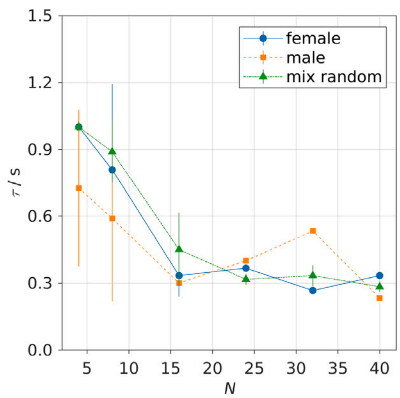
(a) Australia.



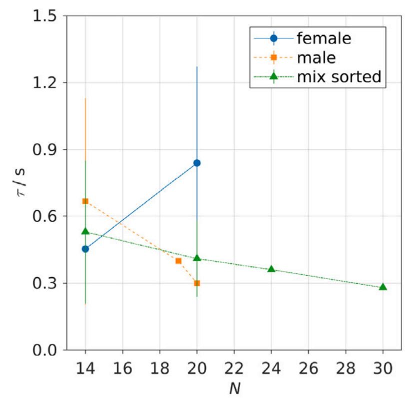
(b) China.



(c) Germany.

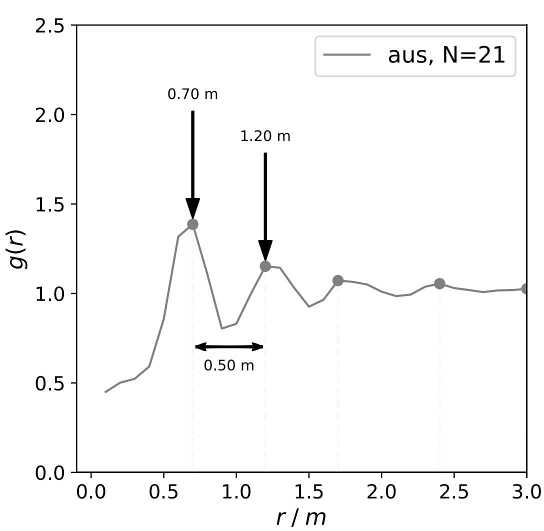


(d) Japan.

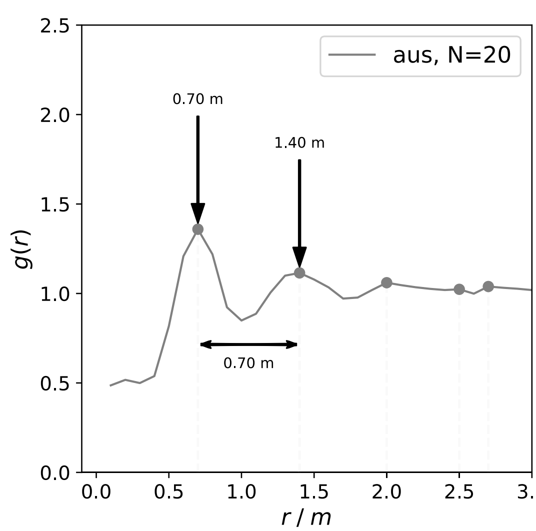


(e) Palestine.

Fig. 9. Variation of time lag over cultures and genders.



(a) Female only run with 21 pedestrians.

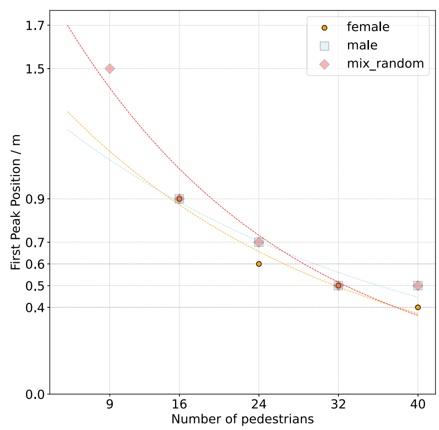


(b) Male only run with 20 pedestrians.

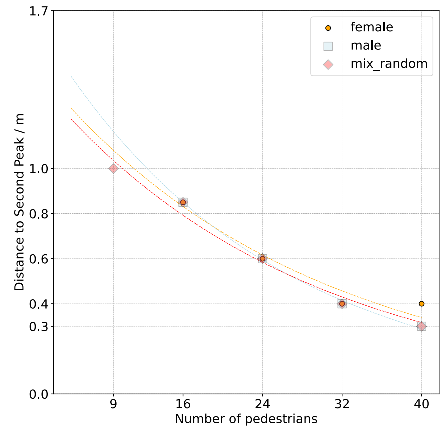
Fig. 10. Distribution functions $g(r)$ per category for Australia. To view $g(r)$ for other countries, densities, and categories, the reader can use the app https://go.fzj.de/genderwalk..

with females showing wider spacing (1.0 m) between subsequent groups than males (0.8 m).

Japan exhibits a consistent pattern: Both females and males start clustering at almost the same distance, with females at 0.76 meters and males at 0.79 m. Their secondary grouping is also nearly identical, with females at 0.72 m and males at 0.71 m. In mixed random groups, clustering occurs slightly later at 0.87 m, with a more compact secondary grouping at 0.68 m. This suggests that the clustering behavior between male and female groups in Japan is generally similar, while mixed random groups demonstrate a more delayed but tighter grouping.



(a) Relationship between initial peak positions and pedestrian count per run.



(b) Interpeak distance as a function of pedestrian density in different runs.

Fig. 11. Japanese pair-distribution metrics: variation with pedestrian count across gender categories.

German pedestrians show gender uniformity in initial clustering (0.8 m), with a subtle difference in the secondary grouping: females form slightly more compact groups (0.7 m) compared to males (0.8 m).

Palestine stands out with the largest initial interpersonal distance (0.9 m) for both genders, significantly exceeding other countries. Notably, Palestinian females exhibit even larger secondary peak distances, indicating strong clustering tendencies with substantial inter-group spacing.

Mixed composition findings. Fig. 12(b) reveals distinct patterns in mixed-gender pedestrian configurations in several countries:

China exhibits notable differences between its mixed compositions. The random configuration shows an initial 0.8 m peak followed by a 0.9 m secondary distance, indicating wider spacing compared to single-gender groups. In contrast, the sorted arrangement, while maintaining the initial peak 0.8 m, shows a reduced secondary distance of 0.7 m, suggesting more uniform grouping when the genders alternate.

Japanese data, available only for the mixed random category, demonstrate an initial peak 0.7 m with a compact secondary distance 0.6 m, which potentially indicates closer interactions in mixed gender scenarios.

Germany presents consistent behavior in both mixed configurations: an initial 0.8 m peak followed by a 0.7 m secondary distance. This uniformity suggests that German pedestrians maintain similar spacing regardless of gender arrangement in mixed groups.

Palestinian data, limited to the mixed sorted configuration, mirrors the gender-separated findings with both initial and secondary peaks at 0.9 m. This consistency across configurations may indicate strong cultural influences on interpersonal spacing that persist even in mixed-gender settings.

These findings highlight significant cultural and gender-based differences in pedestrian spacing. Palestine stands out with larger interpersonal distances, potentially reflecting distinct cultural norms. Japan and Australia demonstrate closer walking distances. The mixing effect in China and Germany reveals more structured behaviors in the mixed sorted condition, suggesting that pedestrians exhibit more regular spacing in this arrangement. Mixed random configurations generally indicate more spontaneous interactions and varied behaviors.

However, we should emphasize that data for some composition for some countries are missing, which limits a comprehensive comparison for all countries and compositions. If we consider the discretization of the bin of 0.1 m, we may conclude that differences in the peak position equal to the bin size may be considered equal.

4. Discussion

Through carrying out consistent experiments in five different countries, we established a strong foundation for reproducibility and model validation. Our data are being considered for inclusion in the RiMEA-benchmark.[3] In addition, we investigated the impact of cultural and gender factors on pedestrian behavior.

Furthermore, our investigation explored the domain of gender composition within pedestrian dynamics. Despite the disagreement discussed in the existing literature on the impact of gender on pedestrian behavior, our systematic empirical analysis offered a different perspective.

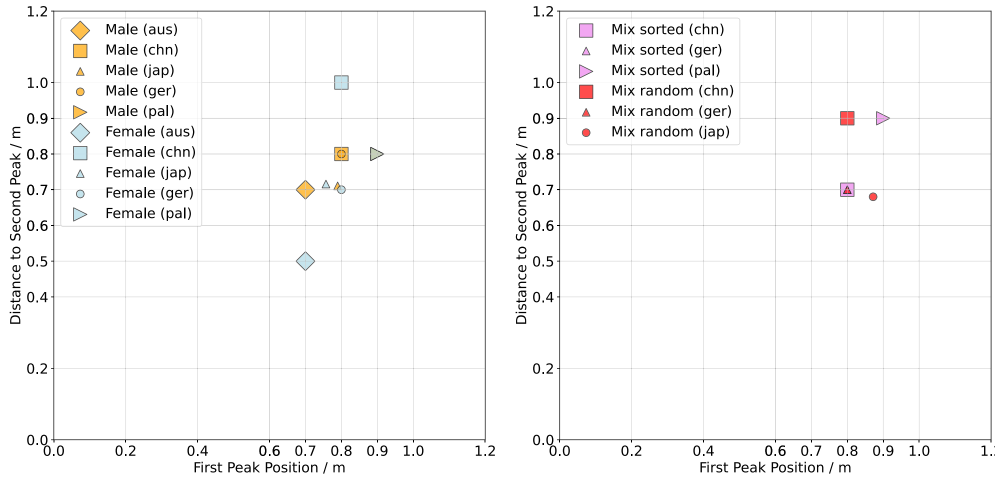
The study presents several key findings, which are summarized in Table 4. In the analysis of fundamental diagrams, no significant deviations were observed, particularly in the bounded regime, as confirmed by KS-statistics. Regarding acceleration behavior, gender had a significant influence on acceleration values in Australia, China and Germany, but not in Japan and Palestine. However, the number of pedestrians significantly affected the time it took them to accelerate, while gender did not.

Proximity analysis revealed that distances between pedestrians were consistent on all curves, regardless of the gender composition of their immediate neighbors and the country considered. Furthermore, the level of interaction and clustering behavior remained consistent between different gender compositions. Lastly, a consistent pattern of pedestrian spacing was observed in various gender compositions and countries.

The study concludes that pedestrian behaviors, such as acceleration and spacing, exhibit consistent patterns across different countries and gender compositions. Specifically, the fundamental diagrams did not show significant deviations, suggesting uniformity in pedestrian dynamics within bounded regimes. Gender influences acceleration in some countries but not others, and pedestrian density affects the timing of acceleration onset. Proximity and interaction patterns remain stable regardless of gender composition or country, indicating universal consistency in pedestrian spacing and clustering behaviors. By decoupling the effects of gender from the experimental configurations, we contribute critical insight to the ongoing discourse on pedestrian dynamics.

Investigations of the transferability of experimental findings in crowd dynamics are still relatively rare, but there is a growing recognition of their importance (Haghani, 2020; Jin et al., 2019). A previous

[3] https://rimea.de/



(a) Female and Male. (b) Mix sorted and mix random.

Fig. 12. Comparison of the distance between the first pick and the second pick across different countries. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Summary of main results by section.

Section	Summary of main results
Section 3.1 Fundamental diagrams	No clear deviations were observed in the resulting fundamental diagrams, especially in the bounded regime, as confirmed by KS-analysis.
Section 3.2 Acceleration and deceleration behavior	Concerning acceleration values, genders had significant influence in Australia, China, and Germany, whereas insignificant in Japan and Palestine. No clear differences were observed in the timing of pedestrians began to accelerate.
Section 3.3 Self-organized structure	The level of interaction and clustering behavior varies across gender compositions and cultures, with some countries showing consistency and others exhibiting distinct patterns between single-gender and mixed groups.

work (Haghani, 2021) has explored external validity, focusing on consistency between independent samples and varying experimental setups. The findings of this study align with previous results, showing significant consistency in behavioral observations across different samples and experimental methods, suggesting the presence of universal and reproducible patterns.

We recommend that, when resources permit, more coordinated experiments across multiple populations be conducted to better understand the extent of universality in crowd behavior, particularly in experimental settings. Such experiments would enhance empirical evidence on transferability and generalizability, providing evidence-based answers to the question of whether experimental findings in crowd research are transferable. Establishing universal patterns in both decision-making and traffic flow-type experiments would significantly boost confidence in this methodology, with major implications for future research and knowledge development in this field.

Data availability

All experiment trajectories are open-access and available as detailed in (Chraibi, 2024).

Software developed to handle and analyze the detailed datasets in this study, along with an interactive interface for data exploration, is available under specific conditions. The source code is openly available on GitHub https://github.com/PedestrianDynamics/gender-experiments (Chraibi et al., 2024) under the MIT license that allows non-commercial utilization, sharing, and modification of the software with proper acknowledgment. To compute density, speed in Section 3.1, and pair distribution in Section 3.3, the Python library (Schrödter et al., 2024) is utilized.

CRediT authorship contribution statement

Mohcine Chraibi: Conceptualization, Writing – original draft, Methodology, Software, Visualization, Writing – review & editing. **Claudio Feliciani:** Conceptualization, Writing – review & editing, Data curation, Funding acquisition, Ressources. **Milad Haghani:** Funding acquisition, Resources, Data curation, Writing – review & editing. **Xiaolu Jia:** Funding acquisition, Writing – review & editing, Methodology, Formal Analysis, Validation. **Jian Ma:** Funding acquisition, Resources, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. KS-distances

The KS distance represents the maximum absolute difference between two empirical cumulative distribution functions. For two cumulative distribution functions $F_1(x)$ and $F_2(x)$, the KS distance D is defined as:

$$D = \max_x |F_1(x) - F_2(x)|. \tag{4}$$

This metric allows for a comparison that is independent of the underlying distribution shapes, making it versatile for analyzing empirical data without assuming specific distribution models. For every density interval, we compute the KS distance between the speed distributions of two data sets that represent distinct countries.

In order to combine the KS distances calculated for each bin into a unified measure of dissimilarity between two countries, we used a weighted mean approach. Here, the weight assigned to each bin (w_i) is based on the number of observations it includes. Given a set of density bins n, each bin i has a KS distance D_i measured between two empirical distributions within that bin. The weighted average D_{avg} of the KS distances across all bins is computed as:

$$D_{\text{avg}} = \frac{\sum_{i=1}^{n} w_i D_i}{\sum_{i=1}^{n} w_i}, \tag{5}$$

where n is the total number of density bins used in the analysis.

This method highlights the significance of density ranges with larger amounts of data, ensuring that the resulting measure predominantly captures the most reliably estimated segments of the distribution. Furthermore, to evaluate the detected variations, we calculated 95% confidence intervals for the KS distances in each category using a bootstrapping method.

This process includes an iterative sampling of the data within each category and re-evaluating the KS distance, resulting in an empirical distribution of the KS statistic from which confidence intervals are established. See Fig. 13.

We observe significant variability in the congested regime, likely due to the emergence of collective phenomena such as stop-and-go waves, which cause differences in speed at high densities. The lowest KS-values are found in the mid-density regime, also known as the bounded regime, where people interact without the restrictions present in the congested regime but still do not move freely as in low-density regimes. This suggests that the interaction mechanisms among people are comparable across countries. In the free-flow regime (low densities), it is expected that KS-values will increase as pedestrians move more freely in this regime. Note that the high spikes at high density in the comparisons with the Palestinian data are due to the fact that these experiments do not include high-density scenarios.

Appendix B. Influence of pedestrian age in Japan individual experiments

Limited to Japan experiments, individual experiments were performed to examine the individual free speed and acceleration. Among the 79 participants (one was late and did not participate in this preliminary free-walking speed experiment), there were 20 female students, 20 male students, 20 elderly male, and 19 elderly female, thus keeping the ratio of each group nearly equal. Considering that our experiments focus on the influence of gender, all the crowd experimental runs were designed to have the same number of elderly and young students to eliminate or at least reduce the influence of age.

Still, we note that age indeed has influence and that students have higher average walking speed and acceleration in our experiments on individual pedestrians. On the one hand, the free speed was calculated when pedestrians walked at a stable speed with $|x| \leq 1.0\,\text{m}$. Fig. 14(a) compares free walking speeds of the elderly and students. The average speeds for the elderly were $1.13 \pm 0.09\,\text{m}\,\text{s}^{-1}$ (female) and $1.14 \pm 0.15\,\text{m}\,\text{s}^{-1}$ (male), and those for the students were $1.29 \pm 0.13\,\text{m}\,\text{s}^{-1}$ (female) and $1.31 \pm 0.17\,\text{m}\,\text{s}^{-1}$ (male).

Analysis of free-speed variations across gender and age groups revealed notable patterns. One-way ANOVA tests did not show significant gender-based differences in free speeds for elderly ($F(39,1) = 0.08$, $p = 0.78 > 0.05$) or students ($F(39,1) = 0.25$, $p = 0.61 > 0.05$). However, age-related disparities were pronounced, with elderly participants demonstrating significantly lower free speeds compared to students, both among females ($F(39,1) = 20.77$, $p = 5.23 \times 10^{-05} < 0.05$) and males ($F(39,1) = 11.92$, $p = 0.0014 < 0.05$).

However, free acceleration was calculated for the period from the initial start of standstill when pedestrians began walking until pedestrians reached a relatively high speed. Here, we arbitrarily calculate the free acceleration for the duration when the speed of the pedestrian i continuously meets $0.1 s_i^{\text{free}} \leq s_i(t) \leq 0.9 s_i^{\text{free}}$, with $s_i(t)$ defined as the speed of pedestrian i at time t and s_i^{free} as the speed of free walking. In Fig. 14(b), the average accelerations of the elderly were $0.39 \pm 0.17\,\text{m}\,\text{s}^{-2}$ (female) and $0.51 \pm 0.37\,\text{m}\,\text{s}^{-2}$ (male) , and those of the students were $0.83 \pm 0.69\,\text{m}\,\text{s}^{-2}$ (female) and $0.75 \pm 0.60\,\text{m}\,\text{s}^{-2}$ (male).

Males and females show similar free acceleration. A one-way ANOVA revealed no significant differences between genders for either the elderly ($F(39,1) = 1.57$, $p = 0.22 > 0.05$) or students ($F(39,1) = 0.10$, $p = 0.76 > 0.05$). Age, however, affects free acceleration differently. Elderly females have significantly lower free acceleration than female students ($F(39,1) = 7.12$, $p = 0.01 < 0.05$). For males, although this age-related difference is not significant ($F(39,1) = 2.34$, $p = 0.13 > 0.05$), the larger box height of the male students over the elderly males in Fig. 14(b) indicates their higher capacity for abrupt acceleration.

In Japanese individual experiments, gender had little influence on free speed and acceleration, consistent with its insignificant effect in crowd experiments. Age influenced both speed and acceleration, but its impact on crowd experiments was negligible because we maintained a consistent ratio of elderly participants to students across all experimental runs. These findings align with previous research, which has shown mixed results for gender's influence depending on the demographic (Dias et al., 2022; Paetzke et al., 2023), while consistently demonstrating a significant effect of age (Cao et al., 2018; Wang et al., 2021).

Appendix C. Proximity analysis

The analysis of pedestrian proximity to immediate neighbors under varying gender compositions across different countries provides insightful perspectives into social dynamics and space utilization in pedestrian flows. When examining the distances between pedestrians in four distinct categories, female, male, mixed random, and mixed sorted, with further subdivisions in mixed categories for neighbors of

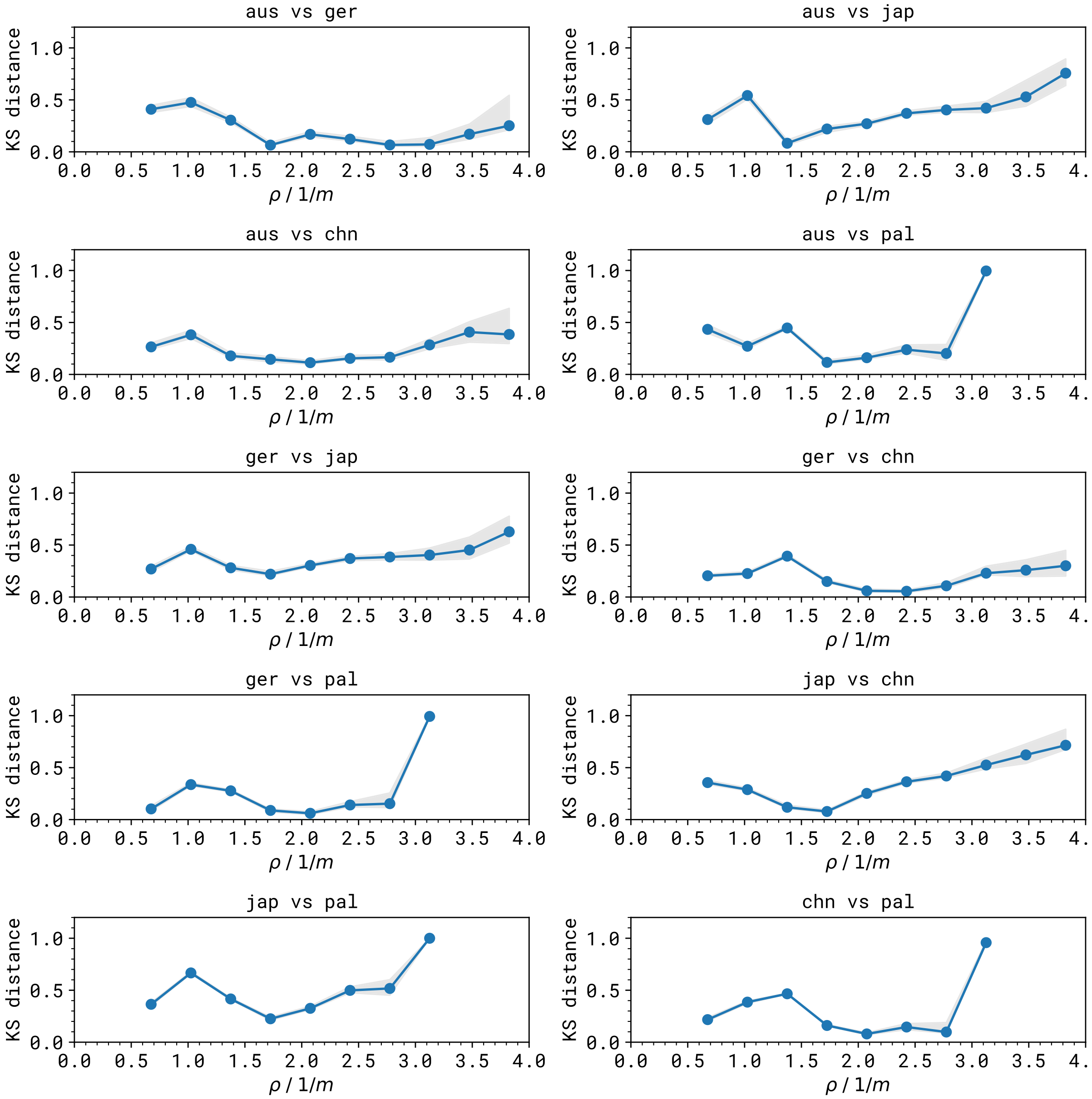


Fig. 13. Visualization of the outcomes from the pairwise comparisons of the weighted KS-distances. Each individual plot illustrates the bin-wise KS distances together with their corresponding confidence intervals for a specific pair of countries.

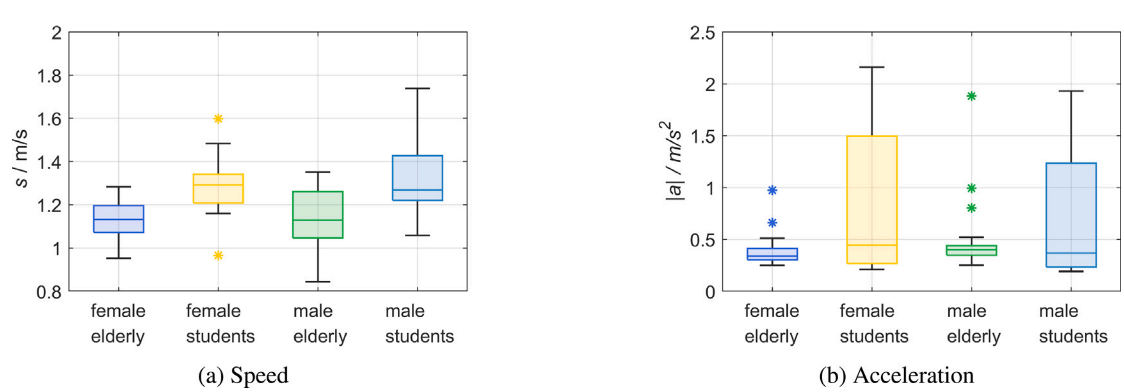
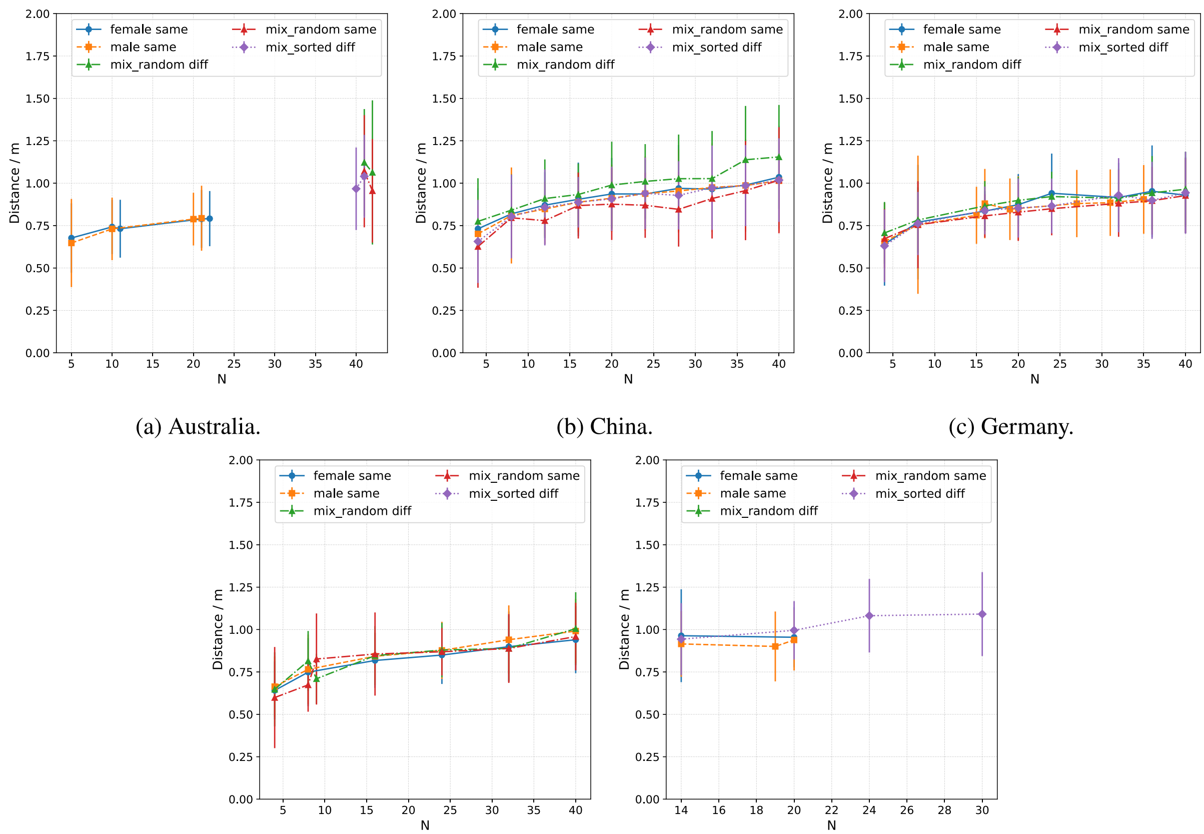


Fig. 14. Comparison of free speed and acceleration over gender and age in Japan experiments.



(a) Australia. (b) China. (c) Germany.

(d) Japan. (e) Palestine.

Fig. 15. Distance variations for different categories across all countries. In the legend, "same" stands for distances among same-gender participants, and "diff" for different genders. In the mix scenario both combinations are possible, although in the case of female and male-only, the "same" is clearly the only possible condition. For the same reason, "same" was not considered in the mix sorted scenario because the preceding pedestrian is always of a different gender.

different and the same gender, the study seeks to elucidate the influence of gender composition on interpersonal distances in pedestrian settings.

We observe in Fig. 15 that all the curves representing the distances between pedestrians, regardless of the gender composition of their immediate neighbors, collapse into a single pattern, suggesting universal behavior in pedestrian spacing that transcends gender distinctions. Although at low density, we observe a high fluctuation, which is due to the lack of interactions among pedestrians and the closed-boundary conditions.

Appendix D. Probability density function distribution of distances

We examine the distance probability density functions in various configurations. In Fig. 16(a), we compare the probability distance function for gender compositions, while in Fig. 16(b), we display the probability distance function for various countries.

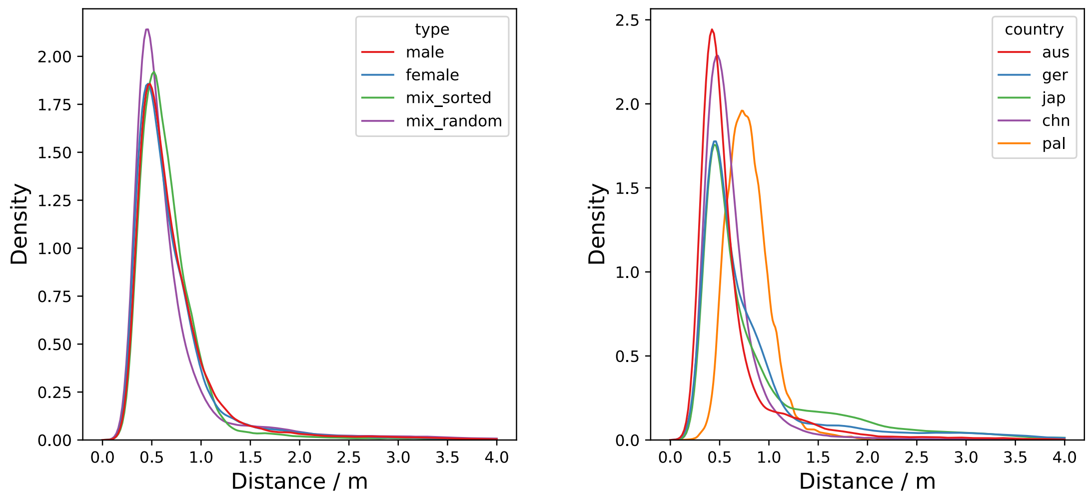
Both figures show Gaussian distribution patterns, with a specific emphasis on gender diversity (female only, male only, mixed-gender groups with random and organized arrangements) and the classification of countries (Australia, China, Germany, Japan and Palestine). The regularity of these distributions indicates a consistent tendency in regulating interpersonal distances, regardless of the group's composition or the cultural origins of the individuals.

There are no apparent variations in the distributions between different groups of compositions or countries, suggesting that gender and cultural differences do not have a substantial impact on how individuals maintain distance in single-file pedestrian movements in this scenario. The lack of any patterns, such as double peaks, in these distributions indicates a consistent pattern of pedestrian spacing that seems to be universal, underscoring the consistent nature of pedestrian behavior in various social and cultural settings, as observed in these experiments.

Appendix E. Symmetry in neighborhood distances

This section explores the spacing patterns that pedestrians maintain with their immediate successor in the direction of movement (referred to as "next") and their immediate predecessor (referred to as "prev"). We analyze the symmetry and variability within the kernel density estimations (KDEs) of these distances across various countries, considering the gender of the neighboring individuals and whether they share the same gender as the pedestrian or a different one.

For Australia, the KDE plot in Fig. 17 shows a concentration around the coordinates (0.5 m, 0.5 m) in a circular pattern, indicating that interactions between different genders occur at a consistent and moderate distance from each other. The circular shape suggests that there is no clear preference for longer distances in the "next" or "prev" measurements, demonstrating symmetry in physical proximity behaviors. In contrast, the plot shows a wider variability and spread along the diagonal for interactions between individuals of the same gender, indicating a wider range of distances being maintained. This suggests a higher level of comfort or variability in physical spacing between pairs of the same gender. In the case of Japanese data (Fig. 18(b)), the significant



(a) PDF by gender category.

(b) PDF by country.

Fig. 16. Probability density function for all gender categories and countries. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

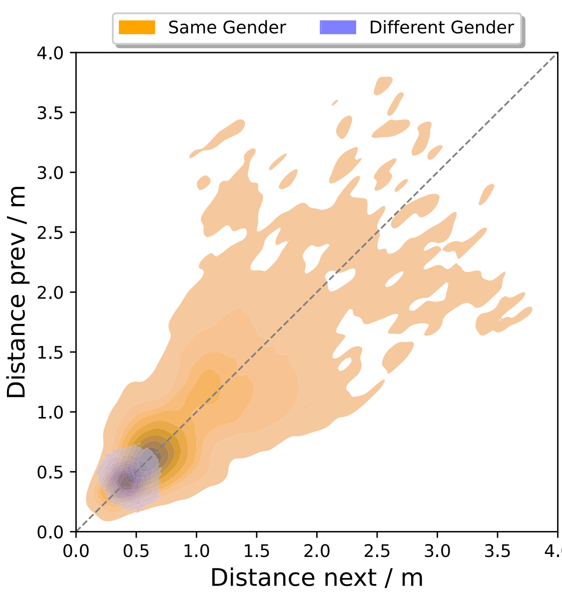


Fig. 17. PDF of distances to the neighbors for Australia. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

wide range of variability in both interactions involving individuals of the same gender and those of different genders implies the existence of a cultural or social norm that does not strictly define the personal space based on gender. The variability in distances reflects a flexible approach to physical distancing, which may be more influenced by situational factors than by the gender of the individuals. A similar trend is observed in the data from Germany (Fig. 18(a)), except for the scenario involving individuals of the same gender, where the distance range is much narrower. This suggests a lack of distinct preferences for the neighboring positions “next” and “prev” in situations where individuals of the same gender are involved.

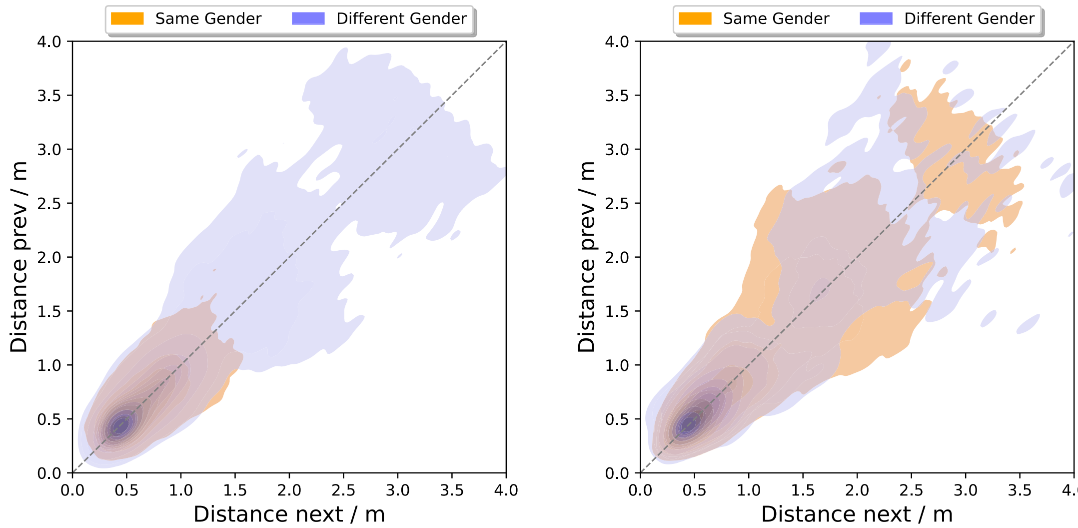
In the case of China (Fig. 19(a)) and Palestine (Fig. 19(b)), we can see a distinct narrow circular pattern centered around specific coordinates (0.5 m, 0.5 m) for China and (0.8 m, 0.8 m) for Palestine. This indicates a more consistent and uniform preference for personal space between genders, suggesting the presence of strong social norms that dictate appropriate social distances with less variation. The slight variation in central points may signify cultural subtleties influencing the perception of comfortable social distances.

The contrast between nations such as Australia and Japan, which exhibit significant variability, and China and Palestine, which demonstrate more uniformity, may be indicative of different attitudes towards personal space and social interactions. Greater variability could suggest adaptability with respect to personal space that can differ significantly depending on the specific context, relationship, or environment. On the other hand, consistency and narrow variations may point towards a more standardized approach to personal space, potentially influenced by stronger or more universally accepted social conventions. Furthermore, the shape of the distribution (circular versus elongated) can offer insight into whether there are distinctions in how distances are maintained when interacting with the “next” neighbor compared to the “prev” neighbor. Circular distributions imply symmetry, indicating that the social norms that govern personal space remain consistent regardless of the direction of the interaction.

To conclude, we also investigate symmetries in distances to neighboring entities, showing variations in distances to adjacent and preceding neighbors among different gender categories. Since we consider these results to be of minor relevance, details are provided in Appendix F.

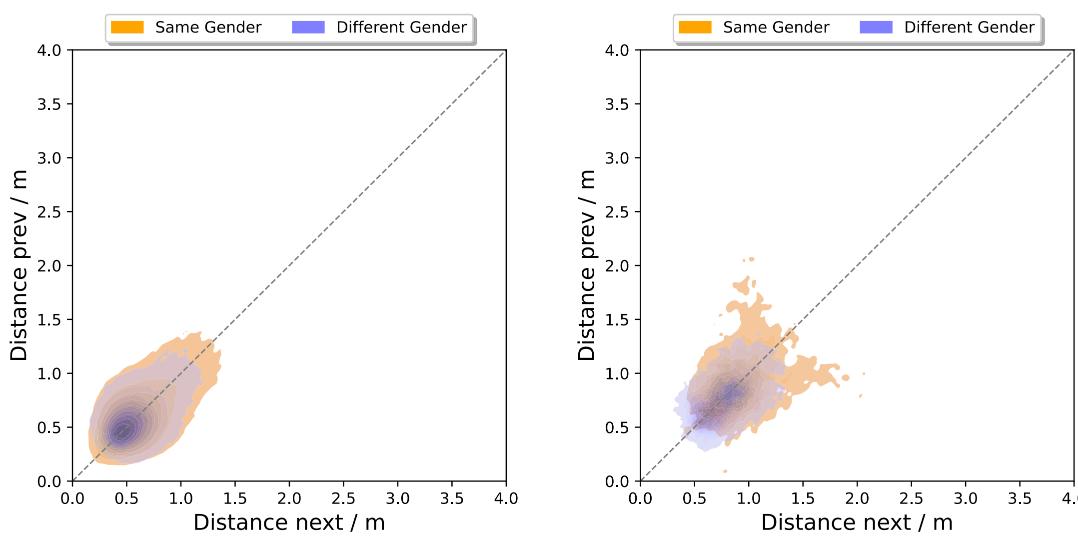
Appendix F. Symmetry of the distribution of distances

To better understand the symmetries represented by the distances in the dataset, we pinpoint specific distances where there is a notable disparity in the occurrences or trends among the groups. At each data point on the x-axis, a positive y-axis value (density differential) signifies that the first group (e.g., female or randomly mixed) exhibits a higher distance density at that particular value compared to the second group (e.g., male or sorted mix). Conversely, a negative value indicates that



(a) Germany (b) Japan

Fig. 18. PDF of distances to the neighbors for Germany and Japan. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



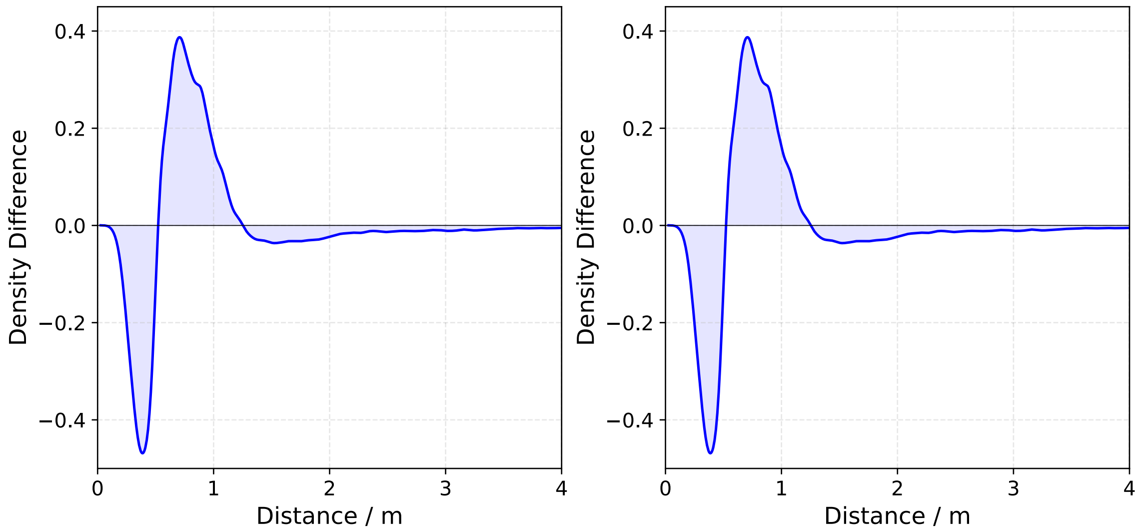
(a) China (b) Palestine

Fig. 19. PDF of distances to the neighbors for China and Palestine. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the second group has a higher density of distances at that value than the first group. A value approaching zero indicates a minimal or negligible divergence in the density of distances at that specific point between the two groups.

The plot in Fig. 20(a) shows the difference in KDE between the female and male categories suggesting a fluctuation in the density differences in the range of values 0 to 4 m. Positive values indicate ranges in which the female category has a higher density (i.e., more prevalent or frequent values) than the male category, and negative values indicate the opposite. If the curve crosses the zero line, it implies that, at those specific values, the density of occurrences switches predominance between female and male. The presence of positive and negative areas suggests differences in the distribution of values between female and male categories, with specific value ranges more common in one gender over the other.

For the graph that compares “mix sorted” to “mix random”, a similar interpretation applies. See Fig. 20(b). The density difference fluctuates throughout the value range, indicating how the distributions of mixed categories differ. Positive regions suggest values where “mix sorted” is denser than “mix random”, implying that these values are more frequent in the “mix sorted” category. In contrast, negative regions would indicate a higher density or frequency of values in “mix random”. Interpretation of crossing points and positive versus negative areas remains consistent with analyzing distribution differences and identifying where one category might be more prevalent or concentrated than the other.



(a) Female vs male.

(b) Mix sorted vs mix random.

Fig. 20. Differences in the probability distribution function between different gender categories.

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