

Received December 2, 2019, accepted January 8, 2020, date of publication February 14, 2020, date of current version February 26, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2973917

# Experimental Investigation on the Alleged Gender-Differences in Pedestrian Dynamics: A Study Reveals No Gender Differences in Pedestrian Movement Behavior

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This work was supported in part by the Arab American University, Palestine, and in part by the German Federal Ministry of Education and Research (BMBF) under Grant 01DH16027. The work of Mohcine Chraibi was supported by the Visiting Professor International Project at the University of Science and Technology of China under Grant 2019A VR35.

**ABSTRACT** Pedestrian dynamics are affected by several factors including pedestrian compositions. In this article, we examine the movement characteristics of Palestinian pedestrians using the fundamental diagram for single-file movement experiments conducted with an emphasis on gender compositions. Our findings show that the mean velocity of exclusively male pedestrians is approximately the same as exclusively female pedestrians. For instance, when the number of pedestrians is 20, the velocities for male and female are  $0.72 \pm 0.10 \text{ ms}^{-1}$  and  $0.71 \pm 0.11 \text{ ms}^{-1}$ , respectively, whereas their velocity decreases gradually if they walk in mixed groups with an average velocity of  $0.61 \pm 0.11 \text{ ms}^{-1}$ . We also compare our findings with other culture-based experiments to demonstrate that pedestrian cultures have an effect on their movement characteristics. Moreover, we demonstrate that age is another factor that affects pedestrians' movement. A comparative analysis is performed between Palestinian and Chinese experiments for this purpose. Our results confirm that for relatively high densities older Chinese pedestrians walk faster than young Palestinians in groups of mixed gender.

**INDEX TERMS** Comparative analysis, fundamental diagram, gender differences, pedestrian dynamics, single-file movement.

## I. INTRODUCTION

Several factors affect the mobility of pedestrians. Among these are building layouts [1], desired destinations, psychological and physiological factors [2], and surroundings (people, obstacles) [3], [4]. Understanding each of these factors plays a crucial role in the development of various application domains such as socially-aware robots [5], autonomous vehicle navigation systems [6] and human trajectory prediction models [7]. Another important factor that needs to be considered when studying pedestrian dynamics is the composition of pedestrian groups, such as age and gender

The associate editor coordinating the review of this manuscript and approving it for publication was Stavros Souravlas<sup>1b</sup>.

compositions among different cultures [8]–[10]. One way to quantitatively describe the effect of these factors is to examine their fundamental diagram (FD) and analyze it. Several recent research papers have analyzed the FD using various forms of single-file movement experiments. Examples of such studies are presented in [10]–[19]. Over the past few years, various studies and experiments have focused on exploring the impact of age [9], [10], [20], [21], gender [10], [22], and culture [8], [23] on pedestrian dynamics. For instance, Chattaraj *et al.* [8] examined the effect of the culture factor on the dynamics of pedestrians in Germany and India. Cao *et al.* [21] studied the dynamics of different age groups in China: young, old, and mixed groups. However, less attention has been paid to date to the characteristics of pedestrians among different gender

groups (female only, male only, and mixed). In a similar line of research, Subaih *et al.* [22] studied the differences of movement characteristics between male and female pedestrians in Palestine. Cao *et al.* [10] measured the velocity and other movement quantities such as headway and density by extracting the data of each gender group, ignoring, however, the effect of group compositions on pedestrian movement characteristics. For instance, the behavior of pedestrians walking within a group of the same gender may be different than that of a group of mixed gender. Furthermore, as reported in [24], a large number of experiments for different cultures under similar conditions are required in order to better understand all the cultural aspects of pedestrian dynamics. We would like to point out that, to the best of our knowledge, this is the first time that research of this type has been conducted in the Arab world, which is dominated by common religious beliefs and cultural attitudes. These factors may be significant for related gender-based issues, including pedestrian dynamics. Consequently, the conclusions from this study may be generalized to other neighboring countries that share similar attributes. Moreover, conducting these experiments in Palestine may establish a foundation for further experiments across other Arab countries to explore potential particularities with regard to the dynamics of pedestrian.

In this paper, we explore the impact of pedestrian compositions – with an emphasis on gender, culture, and age factors – on their movement characteristics. We compare our findings (using single-file movement experiments with mixed-gender groups in Palestine) with other similar works in this domain. Our objective is to analyze data trajectories of mixed gender-based experiments conducted in Palestine [22], Germany [8], India [25], and China [21], and to conduct a comparative analysis using physical pedestrian movement quantities, such as velocity, speed changes for different densities, and headway.

The rest of this paper is organized as follows. In Section II, we review the literature related to the subject of our study. Section III describes the experiments conducted and data extraction procedures. In Section IV, we analyze the results of our experiments and compare these with those obtained from similar experiments taking into consideration the factors of gender, culture, and age. In Section V, we present the conclusions and outline a framework for future research.

## II. RELATED WORK

Various studies to date have examined the characteristics of pedestrian dynamics [2], [26]–[31]. Some of these are observational, focusing on monitoring pedestrian dynamics to analyze their movement characteristics. For instance, Tanaboriboon and Guyano [31] investigated the dynamics of pedestrians in Bangkok, Thailand by collecting speed data from different public areas for various walkways: stairways, sidewalks, and crosswalks using a video camera. They compared the walking rates of Bangkok pedestrians with other pedestrians from Western (UK, US, Canada) and other Asian (Saudi Arabia, India, Thailand, Singapore, and Sri Lanka)

countries. The findings confirmed that the mean walking speed of Thai pedestrians is less than that of pedestrians from Western countries and relatively similar to the mean walking speed of other Asian pedestrians. Another observational study that was conducted in New Zealand [29] examined the impact of environmental and personal factors on the mean walking speeds under different environmental conditions: rural and urban. The results showed that there is an inter-relationship between personal characteristics of pedestrian, environmental characteristics, and physical factors. Also, there is no relationship between the mean walking speed and population size. However, in these studies, the mean speed of pedestrians was averaged,<sup>1</sup> which means we are lacking the precise data required for describing pedestrians' movement on a microscopic level. Moreover, using manual data collection techniques has led to more inaccuracies in the extraction of data trajectories. Furthermore, in the aforementioned studies, the speed of different pedestrian types was measured in a general way without careful isolation of factors that may affect their speeds.

Other studies have relied on laboratory experiments to analyze pedestrian movement quantities by controlling the factors that may have an impact on them. In this context, experiments have been performed to study the microscopic and macroscopic movement characteristics of crowds, such as the relation between velocity and density, jam and stop-and-go-waves, lateral oscillations, etc. [8]–[10], [18], [32]–[37]. For example, Jin *et al.* [18] performed single-file movement experiments to analyze unidirectional pedestrian flow under high-density situations in China. A total of 203 pedestrians were involved in these experiments, where a global density of  $4\text{ m}^{-1}$  was measured. A comparative analysis was conducted against other cultures [8], [25] using a similar set-up. The results showed that the velocities of the Chinese are close to the velocities of Indian pedestrians and higher than those of German pedestrians. These findings were referred to the impact of cultural differences since both the Chinese and Indians are generally used to moving in relatively more populated spaces than their German counterparts. Other experiments focused on pedestrian compositions [9], [10], [21], [24]. For instance, Cao *et al.* [10], [21] examined the properties of different age groups: young, old, and mixed pedestrians. They found that the movement properties and self-adaptive abilities of different age groups vary, and due to these differences, the jam and stop-and-go waves frequently occurred in mixed groups. Moreover, the authors studied the velocity-headway relation and found that in the young group only two linear regimes could be observed. Furthermore, they examined the stepping behavior of different age groups. As stated by the authors, height and gender do not affect the FD. Another experiment of straight corridor unidirectional flow was performed in Hefei, China to study the movement characteristics of elderly pedestrians under different densities [9]. A total of 73 pedestrians of mean age 64.7 years volunteered in

<sup>1</sup>Distance traveled over the traveling time

these experiments. We constructed nine different scenarios by changing the corridor entrance and exit widths to achieve different densities during the experiments and changing the place of measurement inside the corridor. The results were then compared with the experiment on young people conducted in Germany [38]. They showed a marked difference between the movements of the elderly and young pedestrian. Elderly pedestrians walk slower than young pedestrians with a free-flow speed of  $1.28 \text{ ms}^{-1}$  with small step size, and they maintain a greater distance from the wall than their younger counterparts. Another study was conducted by Chattaraj et al. [8] where the authors focused on the effect of the culture factor on pedestrians' behavior. They compared the FDs and dynamic characteristics of two countries: Germany (mixed) and India (males). The results showed that each culture is characterized by different properties. For instance, Indians walk faster than Germans in relatively high-density situations. Additionally, they studied the effect of the corridor length on the FDs and found that the length of the corridor does not affect the FDs. Another similar experiment was performed in Palestine [22] to study pedestrian dynamics based on gender factor. The authors found that both males and females walk in the same velocity within the same gender group.

III. EXPERIMENTS

In this section, we present the set-up and details of our experiments. Then, we describe the steps we carried out for data extraction from video footage using PeTrack [39].

A. EXPERIMENTAL SET-UP

The experiments were performed at the Arab American University in Palestine. We replicated the experiments of [22] for a group of mixed gender (males and females walking together). The shape and dimensions of the set-up are shown in Fig. 1.

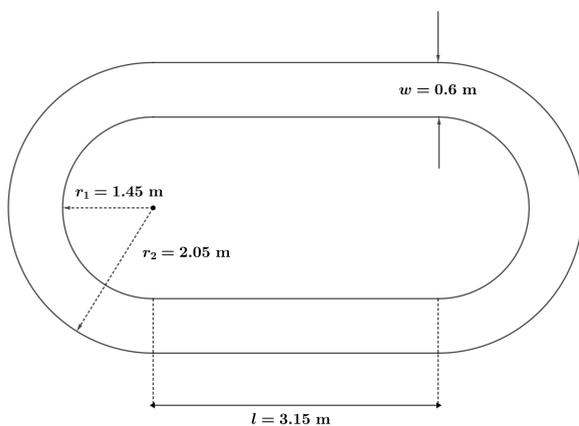


FIGURE 1. Experimental set-up sketch.

A total of 47 participants (26 females and 21 males) from different faculties and departments of the university have participated in the experiments. Different runs were performed

and repeated for mixed-gender experiments. In each run, we gradually increased the number of pedestrians to realize different densities until we reached the critical density. We reached a critical value at  $N = 38$  with a global density of  $\rho = 2.19 \text{ m}^{-1}$  when pedestrians stopped walking and could barely move. Therefore, we reduced the number of pedestrians to  $N = 30$ , so the participants could start walking again. Fig. 2 shows a video frame for one of the runs of the mixed-gender experiments with  $N = 14$  persons.



FIGURE 2. Snapshot for the mixed experiment run ( $N = 14$ ).

Different pedestrians were involved in each run to avoid a bias that might occur if we extract the data for only the same group of pedestrians. Also, each pedestrian walked along the corridor for two to three cycles in each experiment to increase the trajectory data available for measurements. During each run, pedestrians were distributed uniformly along the corridor and instructed to move normally without overtaking. They were positioned in an alternative manner depending on their gender (male, female, male, female,...). Table 1 shows the details of each run.

TABLE 1. Details of Palestine mixed experiment runs. UX: Unidirectional flow mixed experiments.

| Name  | Repetition | Number of participants |      | Global density ( $\text{m}^{-1}$ ) |
|-------|------------|------------------------|------|------------------------------------|
|       |            | Female                 | Male |                                    |
| UX_14 | 4          | 7                      | 7    | 0.81                               |
| UX_20 | 4          | 10                     | 10   | 1.16                               |
| UX_24 | 2          | 12                     | 12   | 1.38                               |
| UX_30 | 2          | 15                     | 15   | 1.73                               |

B. DATA COLLECTION AND EXTRACTION

The trajectories for each pedestrian at different points in time were automatically extracted from videos using PeTrack software. We followed multiple processing pipelines in the software: calibration, recognition, tracking, and analysis to extract precise position data for each pedestrian from the side view. For more information about PeTrack, please refer to [40].

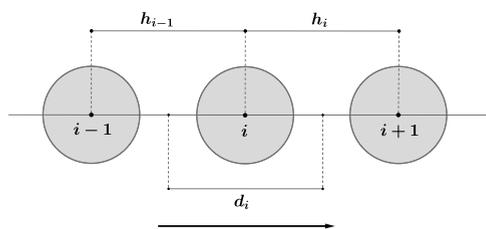
IV. COMPARATIVE ANALYSIS

There are several factors that can affect how pedestrians walk. Physiological (body size and weight) and psychological

factors (future destination, social conventions, and comfort zones) may impact the characteristics of pedestrian dynamics. For instance, when pedestrians move inside crowded places, they move slowly, whereas they walk faster when there are no obstacles or when they are walking alone. Furthermore, pedestrians tend to have a certain “comfort zone” around them. In this section, we examine the factors related to pedestrian compositions: gender, culture, and age that may affect their movement characteristics.

**A. COMPARISON BASED ON GENDER FACTOR**

Male and female participants have different physiological and physiological differences such as body size and behavioral reactions [41]. To discover whether these differences impact their movement characteristics in different compositions, we compared mixed experiments (UX) with male (UM), and female (UF) experiments in [22]. We compared the FDs (density-velocity), velocity-headway, and density-headway relations of the experiments. We used the Voronoi measurement method [42] to calculate the movement basic quantities (density, velocity, and headway) with high accuracy and less fluctuation. As shown in Fig. 3, the headway is defined as the distance between pedestrian  $i$  and her/his predecessor  $i + 1$ . We used the formula of 1D Voronoi method described in [42] to calculate the individual mean velocity and density. The Voronoi space  $d_i$  for pedestrian  $i$  is determined by the sum of half distances between the subject pedestrian and her/his neighbors. In other words, the Voronoi space is the distance between the middle point of the subject pedestrian  $i$  headway, and the middle point of the successor pedestrian  $i - 1$  headway as shown in Fig. 3.



**FIGURE 3.** Illustration of 1D path indicates the distance headway of pedestrians  $i$  and  $i - 1$ , and the Voronoi space of pedestrian  $i$ . The walking direction of the pedestrians is from left to right.

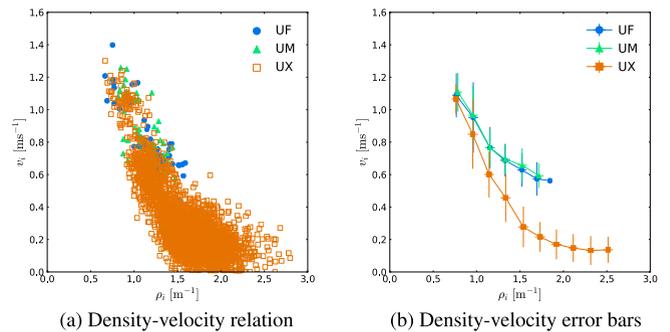
Therefore, the Voronoi density  $\rho_i(t)$  in the measurement section is the inverse of  $d_i(t)$ , and the velocity of pedestrian  $i$  in the measurement section is

$$v_i(t) = \frac{x_i(t + \Delta t/2) - x_i(t - \Delta t/2)}{\Delta t}, \quad (1)$$

where  $\Delta t$  short time interval around  $t$  (10 frames, 0.4 s).

We have defined three phases: start, steady-state, and end phases, respectively. The start phase indicates when pedestrians start moving throughout the corridor. When they begin walking, the velocity is in a transient phase. After some relaxation time, they reached the steady-state phase, where the velocity fluctuations started to decrease. In the end phase,

the velocity started to increase again in some runs when we opened the corridor to allow them to leave (in other runs, we did not record the opening of the corridor). All movement measurements for our experiments were calculated using the steady-state phase only. The density  $\rho_i(t)$  and velocity  $v_i(t)$  data obtained from UF, UM, and UX experiments are plotted in Fig. 4.

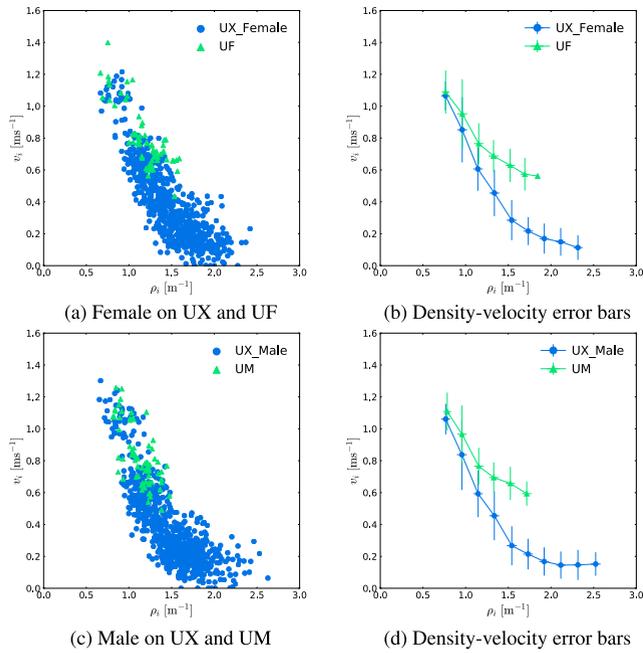


**FIGURE 4.** Left: The FD (density-velocity) relations for different gender groups: UF, UM, and UX. Right: The error bars of velocities for different density ranges, and bins are the mean velocity of each density range.

UF experiments with  $N = 14$ , 20 pedestrians, UM experiments with  $N = 14$ , 20 pedestrians, and UX experiments with  $N = 14$ , 20, 24, 30 pedestrians are used for comparison. By visually inspecting the FDs in Fig. 4, we observe the following. First, a typical negative correlation between the density of pedestrians and the velocity is observed. When the number of pedestrians inside the corridor increased, the velocity decreases, and the pedestrians start to walk more slowly. Second, for different density groups, females and males walk approximately with similar velocities. For example, the mean velocities of females and males when mean density is  $1.5 \text{ m}^{-1}$  are  $0.62 \pm 0.1 \text{ ms}^{-1}$  and  $0.65 \pm 0.01 \text{ ms}^{-1}$ , respectively. Moreover, when mean density is  $1.7 \text{ m}^{-1}$ , the females walk with a mean velocity that equals to  $0.57 \pm 0.1 \text{ ms}^{-1}$  and the males walk with a mean velocity of  $0.59 \pm 0.07 \text{ ms}^{-1}$ . Fig. 4 shows the error bar for mean velocities of UF, UM, and UX with different density ranges. Another result is that the velocity of male and female pedestrians changes significantly if they walk in a group of mixed gender, particularly when the density is greater than  $0.8 \text{ m}^{-1}$ . The mean velocity of pedestrians walking in a mixed group for mean density  $1.5 \text{ m}^{-1}$  is  $0.27 \pm 0.12 \text{ ms}^{-1}$ . As such, we conclude that there is no difference in the way males and females walk in homogeneous groups.

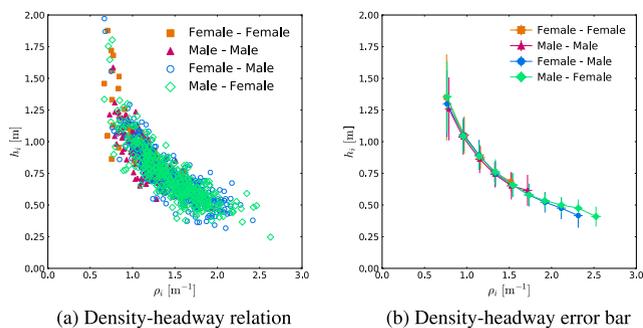
Fig. 4 shows that the velocities of females and males at different densities are approximately similar. However, their velocity changes significantly if they walk in a mixed group. Both males and females reduced their velocity when they walked in a mixed group as shown in Fig. 5.

The change in females’ mean velocity when density is equal to  $1.5 \text{ m}^{-1}$  is  $1.28 \pm 0.12 \text{ ms}^{-1}$ , and for males it is  $0.26 \pm 0.12 \text{ ms}^{-1}$ . These results indicate that Palestinian males and females prefer to reduce their velocity and walk normally when they are walking in a mixed group.



**FIGURE 5. Up: Comparison between the FD (density-velocity) relation of females inside the UX experiments and in UF experiments for different densities. Down: Comparison between the FD relation of males in UX experiments and in UM experiments for different densities.**

Another movement characteristic that we studied here is the "Headway". In general, when people walk, they keep a specific distance from other pedestrians to move forward. As shown in Fig. 6, the pedestrians' headway decreases at the same rate with an increase in the number of pedestrians inside the corridor for all gender groups. For example, for density  $0.7 m^{-1}$ , the females and males have a headway of  $1.3 \pm 0.3 m$  and  $1.25 \pm 0.2 m$ , respectively. For different densities, we obtain different headway values due to the reduction of space inside the measurement section but these are the same for similar densities of different gender groups.

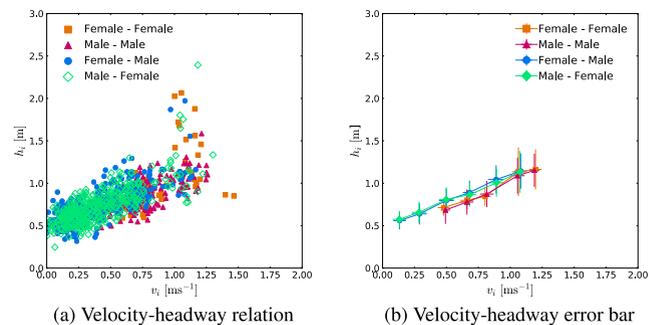


**FIGURE 6. The relation between density and headway for different gender compositions.**

In UX experiments, we measured the headway distance between each pedestrian and the person in front of her/him and the distance between the pedestrian and the person behind her/him to determine whether females maintain a longer headway than males or not when they walk in a mixed group.

From Fig. 6, we can observe that there is no obvious difference between the headway of different densities in UM and UF experiments. For density  $0.7 m^{-1}$ , females keep at a distance of  $1.29 \pm 0.26 m$  while walking, and males keep at a distance of  $1.3 \pm 0.28 m$ . This means that both males and females maintain the same distances if they were walking with other females for the same density and vice versa. By comparing the headway distance of UM experiments with the UX experiments, we can notice that the headway is approximately the same for similar densities. That means if males walk with other males they will keep the same distance as if they walk with other females for the same density and vice versa.

For velocity-headway relation, the results show that the speed of pedestrians varies significantly depending on the gender composition of the group in the experiment. Fig. 7 shows that pedestrians in UX experiments walk slower than pedestrians in UM and UF experiments with the same headway. For example, in order to reach a velocity of  $0.7 ms^{-1}$ , a headway distance of  $0.79 \pm 0.1 m$  is required for females in UF experiments while a headway distance of  $0.9 \pm 0.13 m$  is required for females in UX experiments. The same applies to males who needed  $0.77 \pm 0.14 m$  in UM experiments, and  $0.86 \pm 0.14 m$  in UX experiments. Therefore, we can observe that more distance is needed in UX experiments to reach the same velocities as in UM and UF experiments.



**FIGURE 7. The relation between velocity and headway for different gender compositions.**

**B. COMPARISON BETWEEN CULTURES**

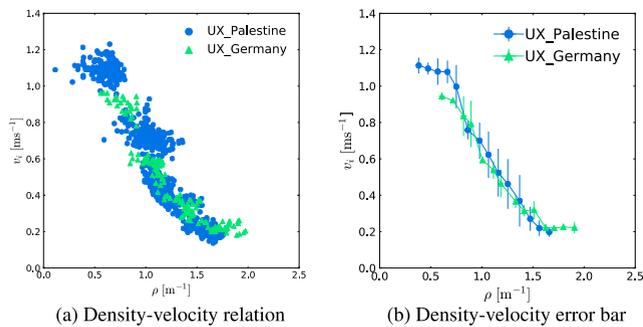
One of the factors that affects the FDs is the culture factor [8]. In this section, we will compare Palestinian experiments with other culture-based experiments such as German [25] and Indian [8] ones. The measured density and velocity of the German experiments are available online in the pedestrian dynamics (PD) data archive.<sup>2</sup> The method used to calculate the density and velocity is described in [25]. Therefore, for better comparability, we used the same method. To analyze the impact of the culture factor on the dynamics, we attempted to keep other factors comparably unchanged. We compared UM experiments (India and Palestine) with approximately the same densities, and compared UX experiments (Germany and

<sup>2</sup>PD data archive: <http://ped.fz-juelich.de/da/2005singleFile>

Palestine) with approximately the same densities, too, since the dynamics of pedestrians change depending on the gender composition within a group (see results of Section IV-A).

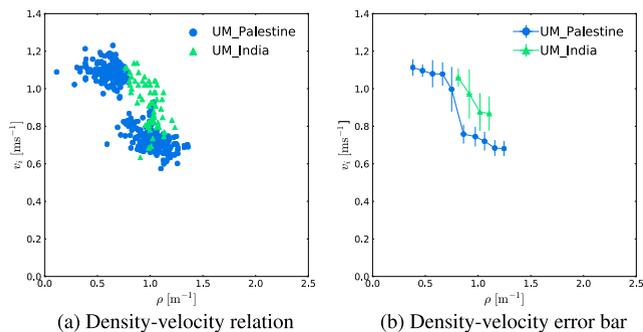
It should be noticed that, in Palestinian UX experiments the pedestrians are arranged in an orderly manner and the number of males in each run equals the number of females (balanced). However, in German UX experiments, pedestrians are ordered randomly and the number of females is not equal to the number of males in each run (unbalanced).

In Fig. 8, the FD relations of Palestinian UX and German UX experiments are presented. We can observe that Germans walk more slowly than Palestinians in UX experiments in low densities. For instance, when the density is equal to  $0.7 m^{-1}$ , Palestinians walk with a velocity of  $0.99 \pm 0.1 ms^{-1}$ , while Germans walk with a velocity of  $0.92 \pm 0.01 ms^{-1}$ .



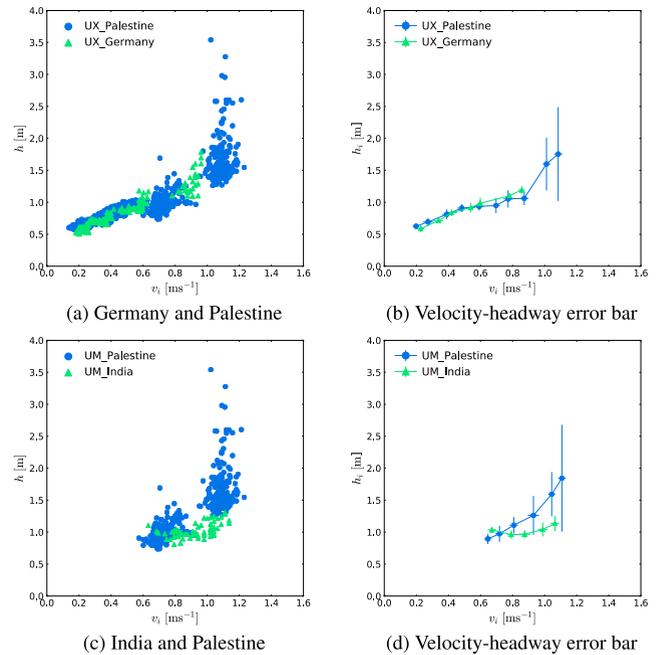
**FIGURE 8.** Left: Relation between the FD (density-velocity) of German and Palestinian UX experiments with approximately the same densities. Right: The error bar of the relation.

Moreover, as shown in Fig. 9, for Indian UM and Palestinian UM experiments, we observed that the Palestinian density in each run is lower than the density of Indians, particularly in the run  $N = 14$ . This means that, compared to Palestinians, Indian males have a smaller comfort zone of personal space when they are walking. Another observation is that the velocity of the Palestinians walking is affected greatly by an increase in density but this is not the case with the Indians, where we can observe a shrinking spaces between the different runs.



**FIGURE 9.** Left: FD (density-velocity) relation between Indian UM and Palestinian UM in single-file movement experiments approximately the same densities. Right: The error bar of the relation.

In this section, we defined the headway as the inverse of the density  $\rho$  as in [25]. Fig. 10 presents the velocity-headway relations between the Palestinian UX and German UX



**FIGURE 10.** Up: Velocity-headway relations in German UX and Palestine UX experiments. Down: Velocity-headway relations of Indian UM and Palestinian UM experiments.

experiments, and the Palestinian UM and Indian UM velocity-headway relations for several densities.

We noticed that Palestinian males maintain more distance when they walk in corridors than Indian males who walk much closely together. Another observation is that German pedestrians in UX experiments walk while keeping at a longer distance than Palestinians in the UX runs in densities approximately between  $0.6 m^{-1}$  and  $0.9 m^{-1}$ . As a result, we can conclude that the culture factor has a significant impact on pedestrian dynamics.

### C. COMPARISON BASED ON AGE FACTOR

In this section, we will examine pedestrian movement properties for different age groups. We compared Palestine UX experiments with Chinese [21] single-file movement experiments with approximately the same densities. In the Chinese experiments there are two groups of experiments based on age: experiments with young participants with a mean age of 17 (16-18 years old) and experiments with older participants with a mean age of 52 (45-73 years old). The trajectory data of the Chinese experiments are publicly available in the pedestrian dynamics data archive.<sup>3</sup>

In previous studies, comparison of different age groups showed differences in the mobility of pedestrians [21]. Younger pedestrians walk faster than older pedestrians in mixed gender groups. Considering the results of [21], we compared Palestinian UX experiments of mean age 19 years with these in China (older with a mean age of 52 and young with a mean age of 17) UX experiments.

<sup>3</sup>China dataset: <http://ped.fz-juelich.de/da/2005singleFile>

TABLE 2. Description of Kolmogrov-Smirnov statistical test results.

| Density-velocity relation (gender)  |                 |              |            |                               |
|-------------------------------------|-----------------|--------------|------------|-------------------------------|
| Sample 1                            | Sample 2        | D-Statistics | D-Critical | Reject/Accept NULL hypothesis |
| UM_14_20                            | UF_14_20        | 0.166        | 0.231      | Accept                        |
| UM_14_20                            | UX_14_20        | 0.387        | 0.174      | Reject                        |
| UF_14_20                            | UX_14_20        | 0.331        | 0.179      | Reject                        |
| UM_14_20                            | UX_Male_14_20   | 0.389        | 0.186      | Reject                        |
| UF_14_20                            | UX_Female_14_20 | 0.298        | 0.192      | Reject                        |
| Velocity-headway relation (gender)  |                 |              |            |                               |
| UF_Female-Female                    | UM_Male-Male    | 0.143        | 0.174      | Accept                        |
| UX_Male-Female                      | UX_Female-Male  | 0.0403       | 0.100      | Accept                        |
| Female-Male + Male-Female           | Female-Female   | 0.434        | 0.139      | Reject                        |
| Female-Male + Male-Female           | Male-Male       | 0.358        | 0.126      | Reject                        |
| Density-velocity relation (culture) |                 |              |            |                               |
| UX_Palestine                        | UX_Germany      | 0.327        | 0.123      | Reject                        |
| UM_Palestine                        | UM_India        | 0.365        | 0.187      | Reject                        |
| Velocity-headway relation (culture) |                 |              |            |                               |
| UX_Palestine                        | UX_Germany      | 0.222        | 0.123      | Reject                        |
| UM_Palestine                        | UM_India        | 0.456        | 0.187      | Reject                        |
| Density-velocity relation (age)     |                 |              |            |                               |
| Palestine_Young19                   | China_Young17   | 0.836        | 0.052      | Reject                        |
| Palestine_Young19                   | China_Old52     | 0.720        | 0.064      | Reject                        |
| Velocity-headway relation (age)     |                 |              |            |                               |
| Palestine_Young19                   | China_Young17   | 0.280        | 0.084      | Reject                        |
| Palestine_Young19                   | China_Old52     | 0.306        | 0.100      | Reject                        |

To compare the FDs of Palestinian-young, Chinese-young, and Chinese-old pedestrians, we calculated the individual mean density and individual mean velocity using the Voronoi method as in Section IV-A. Fig. 11 shows that young Palestinian pedestrians walk slower than young Chinese pedestrians in UX experiments. Also, Palestinian young pedestrians walk faster than Chinese older pedestrians in low densities.

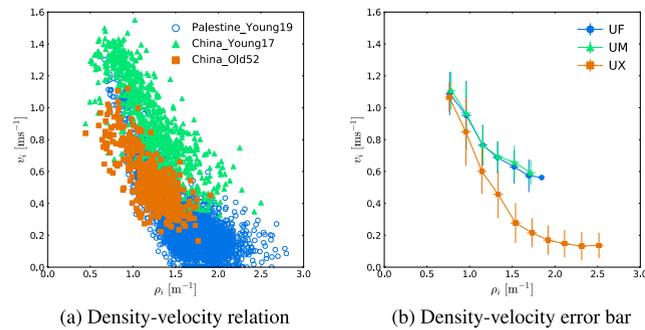


FIGURE 11. Left: FD (density-velocity) relation for three age groups: Palestinian young average age of 19 years, China young average age of 17 years, and China old average age of 52 years. Right: Bars of binning the FD relation.

Surprisingly, old Chinese pedestrians walk faster than Palestinian young pedestrians when they walk in a mixed composition in high densities ( $\rho_i$  more than  $1.45 \text{ m}^{-2}$ ). We assumed that these differences originate by differences in culture and social conventions that define the accepted

comfort zone between pedestrians. This result indicates that while the age factor impacts the movement of pedestrians, it is also governed by the culture factor if we compared different age groups from different cultures.

Fig. 12 shows the velocity-headway relation for the three age compositions. We can notice that when velocity increases, Chinese young pedestrians walk with more available headway in comparison with Chinese old pedestrians and Palestinian young pedestrians. Also, we can notice that the Palestinian young and Chinese old velocities become close when the density equals to  $1.3 \text{ m}^{-2}$ , and they walk with the same headway for velocity lower than  $0.5 \text{ ms}^{-1}$ . For velocities higher than  $0.5 \text{ ms}^{-1}$ , Palestinian young pedestrians

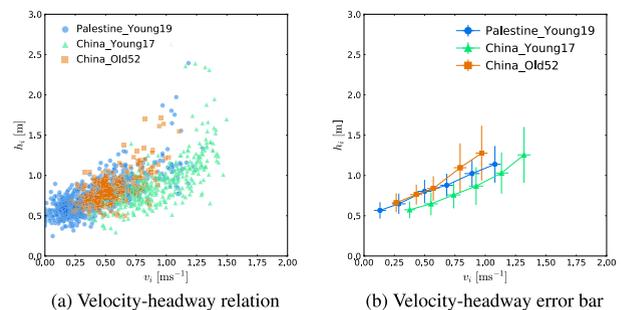


FIGURE 12. Left: Velocity-headway distance relations for different age groups: Palestinians with average age of 19 years, young Chinese with an average age of 17 years, and older Chinese with an average age of 52 years. Right: Bars of binning the velocity-headway relation.

walk with a headway that is shorter than for old Chinese pedestrians. As a result, we conclude that younger pedestrians walk faster with shorter headways than older pedestrians, and that depends on the culture difference.

#### D. HYPOTHESIS TESTING (KOLMOGOROV-SMIRNOV STATISTICAL TEST)

Finally, a Kolmogorov-Smirnov statistical test (two-sample K-S test) was used to test our hypothesis for all parts of the comparison. Here, independent samples of data points were obtained, so that the K-S test was appropriate for hypothesis testing. Table 2 on page 33754 summarizes the results of the test for all data samples that were compared and plotted previously in the comparative analysis section (IV). For the first part of the table - density-velocity relation (gender) - we can observe the null hypothesis to be true when we compare the FD relation for UM and UF experiments: the two samples came from the same distribution. It is statically proven that male and female pedestrians for different densities move with similar velocities on homogeneous experiments. For the second part of the table - velocity-headway relation (gender) - the null hypothesis was accepted when we compared the velocity-headway relation for the female and male experiments. This means that both female and male pedestrians need the same headway to move forward at a specific velocity. Similarly, the headway needed for male pedestrians to keep moving forward in mixed experiments (UX\_Male-Female) is the same as for females in mixed experiments (UX\_Female-Male). Otherwise, all the rejected relations mean that the two samples compared originate from different distributions. Therefore, there are differences between the movement relations that have been compared as stated previously in the comparative analysis part.

#### V. CONCLUSION AND FUTURE WORK

In this work, we discussed the main factors that impact pedestrian dynamics, specifically the composition of pedestrian crowds. Our single-file movement experiments focused on gender, culture, and age factors and were compared to German, Indian and Chinese experiments. We found that with exclusively male and female groups, gender has no effect on pedestrians' movement. However, the velocity changes in mixed groups. When male and female pedestrians walked in a mixed-gender group, they started to reduce their velocities due to social conventions. Moreover, we found that each culture has its own mobility properties. Palestinian pedestrians walk slower than Indian pedestrians and also have a smaller comfort zone of personal space required, and they walk faster than German pedestrians for the same density. Finally, we found that the age factor has a significant impact on the dynamics of pedestrians. Older participants moved slower than younger ones for different densities. Surprisingly, we found that old Chinese pedestrians walk faster than younger pedestrians from Palestine on high densities. The results produced by this study have revealed some interesting and important facts about the gender's impact on

pedestrians' movement behavior: it was generally believed that female pedestrians have different movement behaviors than male pedestrians due to socio-cultural influences. However, in this study we could not confirm this assumption and found that female participants showcase similar macroscopic characteristics as male participants. For future work, more experimental data are required to investigate higher and lower densities for both male and female experiments. Moreover, studying more movement characteristics such as the step size and frequency for different gender groups will contribute to a more comprehensive understanding of gender influence or its absence on the movement of pedestrians in groups.

#### ACKNOWLEDGMENT

The authors would like to thank Arab American University, Palestine, for their support during the preparation of the experiments.

#### REFERENCES

- [1] J. Zhang, *Pedestrian Fundamental Diagrams: Comparative Analysis of Experiments in Different Geometries*, vol. 14. Jülich, Germany: Forschungszentrum Jülich, 2012.
- [2] G. Zeng, A. Schadschneider, J. Zhang, S. Wei, W. Song, and R. Ba, "Experimental study on the effect of background music on pedestrian movement at high density," *Phys. Lett. A*, vol. 383, no. 10, pp. 1011–1018, Mar. 2019.
- [3] C. Appert-Rolland, J. Pettré, A.-H. Olivier, W. Warren, A. Duigou-Majumdar, E. Pinsard, and A. Nicolas, "Experimental study of collective pedestrian dynamics," 2018, *arXiv:1809.06817*. [Online]. Available: <http://arxiv.org/abs/1809.06817>
- [4] A. Garcimartín, D. Maza, J. M. Pastor, D. R. Parisi, C. Martín-Gómez, and I. Zuriguel, "Redefining the role of obstacles in pedestrian evacuation," *New J. Phys.*, vol. 20, no. 12, Nov. 2018, Art. no. 123025.
- [5] A. Bera, T. Randhavane, and D. Manocha, "The emotionally intelligent robot: Improving socially-aware human prediction in crowded environments," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit. Workshops*, 2019, pp. 1–6.
- [6] A. Rasouli and J. K. Tsotsos, "Autonomous vehicles that interact with pedestrians: A survey of theory and practice," *IEEE Trans. Intell. Transp. Syst.*, to be published.
- [7] A. Alahi, K. Goel, V. Ramanathan, A. Robicquet, L. Fei-Fei, and S. Savarese, "Social LSTM: Human trajectory prediction in crowded spaces," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit. (CVPR)*, Jun. 2016, pp. 961–971.
- [8] U. Chattaraj, A. Seyfried, and P. Chakraborty, "Comparison of pedestrian fundamental diagram across cultures," *Adv. Complex Syst.*, vol. 12, no. 03, pp. 393–405, Jun. 2009.
- [9] X. Ren, J. Zhang, W. Song, and S. Cao, "The fundamental diagrams of elderly pedestrian flow in straight corridors under different densities," *J. Stat. Mech.*, vol. 2019, no. 2, Feb. 2019, Art. no. 023403.
- [10] S. Cao, J. Zhang, W. Song, C. Shi, and R. Zhang, "The stepping behavior analysis of pedestrians from different age groups via a single-file experiment," *J. Stat. Mech.*, vol. 2018, no. 3, Mar. 2018, Art. no. 033402.
- [11] Q. Wang, W. Song, J. Zhang, L. Lian, and S. Lo, "Experimental study on single-file movement with different stop distances," in *Proc. 11th Asia-Oceania Symp. Fire Sci. Technol.*, G.-Y. Wu, K.-C. Tsai, and W. K. Chow, Eds. Singapore: Springer Singapore, 2020, pp. 241–253.
- [12] J. Sun, S. Lu, S. Lo, J. Ma, and Q. Xie, "Moving characteristics of single file passengers considering the effect of ship trim and heeling," *Phys. A, Stat. Mech. Appl.*, vol. 490, pp. 476–487, Jan. 2018. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0378437117307641>
- [13] Q. Wang, W. Song, J. Zhang, S. Wang, C. Wu, and S. Lo, "Understanding single-file movement with ant experiments and a multi-grid CA model," *Phys. A, Stat. Mech. Appl.*, vol. 513, pp. 1–13, Jan. 2019. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0378437118309555>

- [14] Y. Ma, Y. Y. Sun, E. W. M. Lee, and R. K. K. Yuen, "Pedestrian stepping dynamics in single-file movement," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 98, no. 6, Dec. 2018. [Online]. Available: <https://link.aps.org/doi/10.1103/PhysRevE.98.062311>
- [15] S. Cao, P. Wang, M. Yao, and W. Song, "Dynamic analysis of pedestrian movement in single-file experiment under limited visibility," *Commun. Nonlinear Sci. Numer. Simul.*, vol. 69, pp. 329–342, Apr. 2019. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S1007570418303228>
- [16] S. Gulhare, A. Verma, and P. Chakroborty, "Comparison of pedestrian data of single file movement collected from controlled pedestrian experiment and from field in mass religious gathering," *Collective Dyn.*, vol. 3, pp. 1–14, Jun. 2018. [Online]. Available: <https://collective-dynamics.eu/index.php/cod/article/view/A16>
- [17] S. Huang, T. Zhang, S. Lo, S. Lu, and C. Li, "Experimental study of individual and single-file pedestrian movement in narrow seat aisle," *Phys. A, Stat. Mech. Appl.*, vol. 509, pp. 1023–1033, Nov. 2018. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0378437118308045>
- [18] C.-J. Jin, R. Jiang, R. Li, and D. Li, "Single-file pedestrian flow experiments under high-density conditions," *Phys. A, Stat. Mech. Appl.*, vol. 531, Oct. 2019, Art. no. 121718.
- [19] S. Huang, R. Wei, S. Lo, S. Lu, C. Li, C. An, and X. Liu, "Experimental study on one-dimensional movement of luggage-laden pedestrian," *Phys. A, Stat. Mech. Appl.*, vol. 516, pp. 520–528, Feb. 2019. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0378437118311646>
- [20] J. Wang, W. Weng, M. Boltes, J. Zhang, A. Tordeux, and V. Ziemer, "Step styles of pedestrians at different densities," *J. Stat. Mech.*, vol. 2018, no. 2, Feb. 2018, Art. no. 023406.
- [21] S. Cao, J. Zhang, D. Salden, J. Ma, C. Shi, and R. Zhang, "Pedestrian dynamics in single-file movement of crowd with different age compositions," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 94, no. 1, Jul. 2016, Art. no. 012312.
- [22] R. Subaih, M. Maree, M. Chraibi, S. Awad, and T. Zanoon, "Gender-based insights into the fundamental diagram of pedestrian dynamics," in *Proc. Int. Conf. Comput. Collective Intell.* Hendaye, France: Springer, 2019, pp. 613–624.
- [23] M. K. Biswal, "Comparison of pedestrian fundamental diagram: A cultural and gender aspect," Ph.D. dissertation, Dept. Civil Eng., Nat. Inst. Technol., Odisha, India, 2014.
- [24] W. Song, W. Lv, and Z. Fang, "Experiment and modeling of microscopic movement characteristic of pedestrians," *Procedia Eng.*, vol. 62, pp. 56–70, Jan. 2013.
- [25] A. Seyfried, B. Steffen, W. Klingsch, and M. Boltes, "The fundamental diagram of pedestrian movement revisited," *J. Stat. Mech., Theory Exp.*, vol. 2005, no. 10, 2005, Art. no. P10002.
- [26] N. W. F. Bode, M. Chraibi, and S. Holl, "The emergence of macroscopic interactions between intersecting pedestrian streams," *Transp. Res. B, Methodol.*, vol. 119, pp. 197–210, Jan. 2019.
- [27] R. Ye, M. Chraibi, C. Liu, L. Lian, Y. Zeng, J. Zhang, and W. Song, "Experimental study of pedestrian flow through right-angled corridor: Uni- and bidirectional scenarios," *J. Stat. Mech.*, vol. 2019, no. 4, Apr. 2019, Art. no. 043401.
- [28] M. Haghani, M. Sarvi, Z. Shahhoseini, and M. Boltes, "Dynamics of social groups' decision-making in evacuations," *Transp. Res. C, Emerg. Technol.*, vol. 104, pp. 135–157, 2019.
- [29] K. K. Finnis and D. Walton, "Field observations to determine the influence of population size, location and individual factors on pedestrian walking speeds," *Ergonomics*, vol. 51, no. 6, pp. 827–842, Jun. 2008.
- [30] M. S. Tarawneh, "Evaluation of pedestrian speed in Jordan with investigation of some contributing factors," *J. Saf. Res.*, vol. 32, no. 2, pp. 229–236, Jun. 2001.
- [31] Y. Tanaboriboon and J. A. Guyano, "Analysis of pedestrian movements in Bangkok," *Transp. Res. Rec.*, vol. 1294, pp. 52–56, 1991.
- [32] J. Ma, W.-G. Song, Z.-M. Fang, S.-M. Lo, and G.-X. Liao, "Experimental study on microscopic moving characteristics of pedestrians in built corridor based on digital image processing," *Building Environ.*, vol. 45, no. 10, pp. 2160–2169, Oct. 2010.
- [33] L. Lian, X. Mai, W. Song, Y. K. K. Richard, Y. Rui, and S. Jin, "Pedestrian merging behavior analysis: An experimental study," *Fire Saf. J.*, vol. 91, pp. 918–925, Jul. 2017.
- [34] U. Chattaraj, P. Chakroborty, and A. Subhashini, "Empirical studies on impacts of obstacle inside corridor on pedestrian flow," *Procedia-Social Behav. Sci.*, vol. 104, pp. 668–677, Dec. 2013.
- [35] J. Zhang and A. Seyfried, "Experimental studies of pedestrian flows under different boundary conditions," in *Proc. 17th Int. IEEE Conf. Intell. Transp. Syst. (ITSC)*. Oct. 2014, pp. 542–547.
- [36] Y. Zhao, T. Lu, M. Li, and L. Tian, "The self-slowing behavioral mechanism of pedestrians under normal and emergency conditions," *Phys. Lett. A*, vol. 381, no. 37, pp. 3149–3160, Oct. 2017.
- [37] X. Liu, W. Song, and J. Zhang, "Extraction and quantitative analysis of microscopic evacuation characteristics based on digital image processing," *Phys. A, Stat. Mech. Appl.*, vol. 388, no. 13, pp. 2717–2726, 2009.
- [38] J. Zhang, W. Klingsch, A. Schadschneider, and A. Seyfried, "Transitions in pedestrian fundamental diagrams of straight corridors and T-junctions," *J. Stat. Mech.*, vol. 2011, no. 06, Jun. 2011, Art. no. P06004.
- [39] M. Boltes and A. Seyfried, "Collecting pedestrian trajectories," *Neurocomputing*, vol. 100, pp. 127–133, Jan. 2013.
- [40] M. Boltes, J. Schumann, and D. Salden, "Gathering of data under laboratory conditions for the deep analysis of pedestrian dynamics in crowds," in *Proc. 14th IEEE Int. Conf. Adv. Video Signal Based Surveill. (AVSS)*, Aug. 2017, pp. 1–6.
- [41] D. Helbing and P. Molnár, "Social force model for pedestrian dynamics," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 51, no. 5, pp. 4282–4286, Jul. 2002.
- [42] J. Zhang, W. Mehner, S. Holl, M. Boltes, E. Andresen, A. Schadschneider, and A. Seyfried, "Universal flow-density relation of single-file bicycle, pedestrian and car motion," *Phys. Lett. A*, vol. 378, no. 44, pp. 3274–3277, Sep. 2014.



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