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# Group Dynamics in Pedestrian Crowds
## Estimating Proxemic Behavior

Andrea Gorrini, Stefania Bandini, and Majid Sarvi

**Recent crowd disasters highlight the importance of properly planning and designing large urban events and public spaces to enhance the safety of people in a crowd during evacuations. Pedestrian crowd dynamics are empirically investigated with an interdisciplinary approach (i.e., social sciences, computer science, and traffic engineering) focusing on the effect of groups and their proxemic behavior and interactions while walking. Empirical evidence achieved from urban in-field observations and laboratory experiments are presented and compared. Results indicate that the proxemic behavior of walking groups has a negative effect on walking speed when flow is irregular (primarily because of the need for members to maintain spatial cohesion during locomotion). These results have important implications for the design of common metrics to characterize spatial interactions among pedestrians and for the validation of models to replicate crowd dynamics that consider the effects of groups under normal and emergency conditions.**

Interest in studying crowd behavior started in the late 19th century, inspired mainly by increasing urbanization and the consequent need to manage public order in the event of riot or revolution (*1*). Since, the research field has consolidated as a result of its interdisciplinary approach (e.g., traffic engineering, computer science, applied mathematics, social science, and urban planning) and its ability to provide practical results that contribute to more efficient, safer management of large urban events and public spaces (*2*). Recent crowd disasters (e.g., the Kiss nightclub fire on Jan. 27, 2013, in Santa Maria, Rio Grande do Sul, Brazil, where 242 people died and more than 168 people were seriously injured, and the stampede during the Love Parade in Duisburg, Germany, on July 24, 2010, where 21 people died and 510 others were seriously injured) have made it clear that proper planning and design of mass gathering places is crucial to ensure crowd safety in the event of an evacuation.

Research on modeling and simulating microscopic interactions among pedestrians and their surrounding environments under ordinary and emergency conditions is getting considerable attention as a result (*3–9*). Moreover, studies have highlighted the importance of considering crowd dynamics as characterized by the presence of groups (*10, 11*), defined as two or more people who interact to achieve a shared goal (*12*). Under ordinary and emergency conditions, egress and evacuation times are influenced by the presence of groups, which move as block formations in a crowd with an order of evacuation that other pedestrians cannot avoid (*13, 14*).

In the context of previous crowd studies carried out by the authors (*15, 16*), this work aims to support the application of the general framework of proxemics (i.e., human spatial behavior during social interactions) to meaningfully measure the effect of the dynamic regulation of distances between persons walking in groups on whole-crowd dynamics (*17*). This work combines empirical contributions from in-field observations in an urban scenario and an experimental investigation in a laboratory setting to compare differences in walking path and speed between single pedestrians and groups during normal, orderly crowd egress flows. Because of the proposed interdisciplinary approach, the achieved results have important implications for the design of common metrics to characterize spatial interactions among pedestrians and for the validation of models to replicate overall crowd dynamics that consider the effects of groups (*18*). The final aim of this research effort is to contribute to the design of applicative strategies to increase the efficiency of managing pedestrian circulation dynamics in urban scenarios by offering optimized architectural solutions to ensure the spatial efficiency of facilities (i.e., services, comfort, and safety).

This work is organized as follows. First, the proxemic behavior of walking groups is described. Then, the results from an in-field observation of pedestrian crowd dynamics in an urban scenario are presented, with particular reference to level of service (LOS), flow composition, group proxemic behavior, trajectory, and walking speed. Next, results achieved in an experimental investigation in a laboratory setting are presented, focusing on the LOS and walking speeds of single pedestrians and of persons in groups. The paper ends with final remarks, comparisons of results, and suggestions for future developments.

## PROXEMIC BEHAVIOR OF WALKING GROUPS

In walking situations, the dynamic regulation of interpersonal distances is significantly determined by the physical constraints induced by other pedestrians and the environment. Under high-density conditions, which are characterized by turbulence and competitive interactions among pedestrians due to a lower degree of freedom for spatial positioning, individual proxemic behavior is based on the need to avoid collision with oncoming pedestrians. Furthermore, the proxemic behavior of walking groups is characterized by the need to maintain spatial cohesion among members to facilitate social interaction and communication during locomotion (*19*).

As Moussaïd et al. (*11*) and Costa (*20*) demonstrate, the proxemic behavior of groups during locomotion spontaneously produces

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(a) (b) (c)

FIGURE 1 Typical patterns of group proxemic behavior while walking: (*a*) line abreast, (*b*) V-like, and (*c*) riverlike.

typical spatial arrangements or patterns that depend on the density level in the environment (Figure 1). Under low-density conditions, small groups (e.g., triads) tend to walk alongside each other, in a line perpendicular to the walking direction (i.e., a line-abreast pattern). As density increases, the walking formation becomes V-like, with the middle individual positioned slightly behind the lateral individuals, in a misaligned pattern that facilitates social interaction and communication within the group but reduces walking speed. Under high-density conditions, the spatial distribution of the group becomes characterized by the presence of a leader who guides the other members in crossing the space in a riverlike pattern. Groups with larger distributions (more than three members) tend to split themselves into single individuals, dyads, and triads or form other shapes (e.g., rhombus, sphere, or ellipse).

## URBAN IN-FIELD OBSERVATION

### Scenario Analysis

Pedestrian crowd dynamics were observed (and recorded) on Saturday, Nov. 24, 2012, from 2:50 to 4:10 p.m. at Galleria Vittorio Emanuele II, a shopping mall in Milan, Italy. This location was determined ideal because many people pass through for shopping, entertainment, and tourism purposes in the center of Milan. In addition, the setting allows the positioning of equipment on a balcony (which surrounds the inside from about 10 m high) to achieve a quasi zenith view of the walkway, limit the distortion of video images and the occlusion of trajectories, and avoid influencing the behavior of the observed pedestrians. Moreover, a geometric design in the pavement permits researchers to assign spatial reference points that allow postprocessing the video images and analyzing the data with the inclined perspective. Finally, the steel-and-glass roof covering the entire gallery obviates the presence of umbrellas that might have partially occluded pedestrians on a rainy day and thereby compromised the survey's success (Figure 2).

### Method

The observation team was composed of four people. The video equipment consisted of two professional full high-definition video cameras with tripods. Only a 12.8- × 12.8-m square (163.84 $m^2$) of the walkway was considered for data analysis. To enable this analysis, the inner space of the selected area was discretized in cells by superimposing an alphanumeric grid of 1,024 squares, each 0.4 × 0.4 m, on the video images (Figure 2).

### Results

#### *Level of Service*

The density level of the environment was estimated by counting the number of people (7,773) walking through a certain area (12.8 m) during a certain time (from 2:50 to 4:10 p.m.) according to *Highway Capacity Manual* and walkway LOS criteria (*21, 22*). The average flow rate corresponded to LOS B (7.78 pedestrians/min/m), which is associated with an irregular flow under low- to medium-density conditions (Figure 3). Local distributions of medium- to high-density conditions were detected, representing large tourist groups moving in opposite directions.

#### *Flow Composition and Group Proxemic Behavior*

A 15-min subset was extracted (1 min every 5 min). A total of 1,645 pedestrians were sampled, of which 84.19% arrived in groups (43.65% dyads, 17.14% triads, and 23.40% groups of four or more) and 15.81% were single pedestrians. Groups were identified in the stream of passersby on the basis of nonverbal (visual contact, body orientation, gesticulation, and spatial cohesion) and verbal communication among members (*20*). To evaluate these proxemic arrangements, the coder was encouraged to rewind the video and determine the most frequent spatial layout:

(a)

(b)

**FIGURE 2** Galleria Vittorio Emanuele II in Milan, Italy: (*a*) overview of the walkway and (*b*) snapshot from recorded video images with superimposed alphanumeric grid for data analysis.

- 94.43% of dyads walked in a line-abreast pattern, 5.57% in a riverlike pattern;
- 31.91% of triads walked in a line-abreast pattern, 9.57% in a riverlike pattern, and 58.51% in a V-like pattern; and
- 29.61% of groups of four walked in a line-abreast pattern, 3.19% in a riverlike pattern, and 10.39% in a V-like pattern; 10.39% featured a triad followed by a single person, 6.23% a single individual followed by a triad, 7.79% a rhombuslike pattern in which one person headed the group followed by a dyad and a single person, and 32.47% two dyads.

### *Walking Path, Trajectory, and Walking Speed*

A 122-person sample was observed during LOS B (to focus on irregular pedestrian flow under low- to medium-density conditions): 30 singles, 15 dyads, 10 triads, and eight groups of four. The alphanumeric grid was used to manually track trajectories (where the center of the cell occupied by the feet of a pedestrian is considered the actual position; Figure 4) and measure the average paths and speeds (i.e., the distance traversed during a certain time period) of

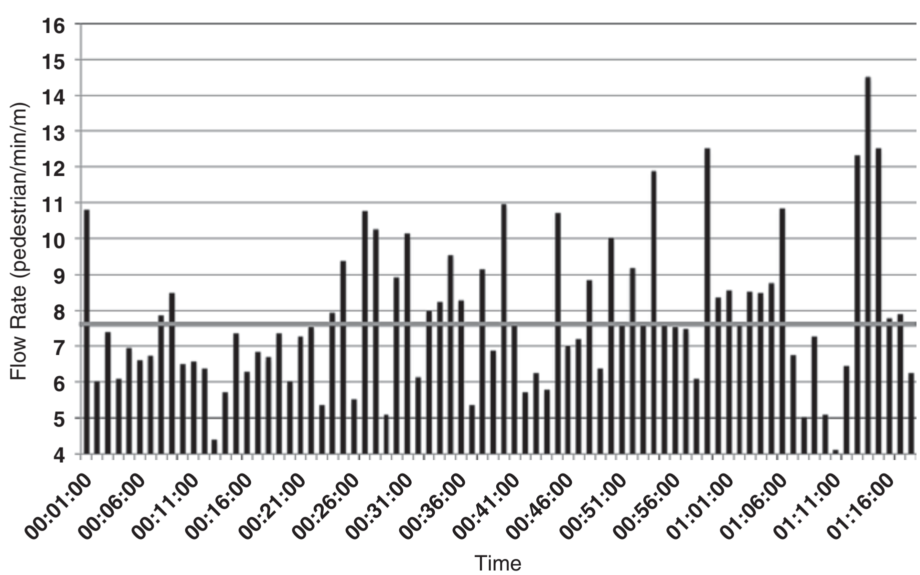
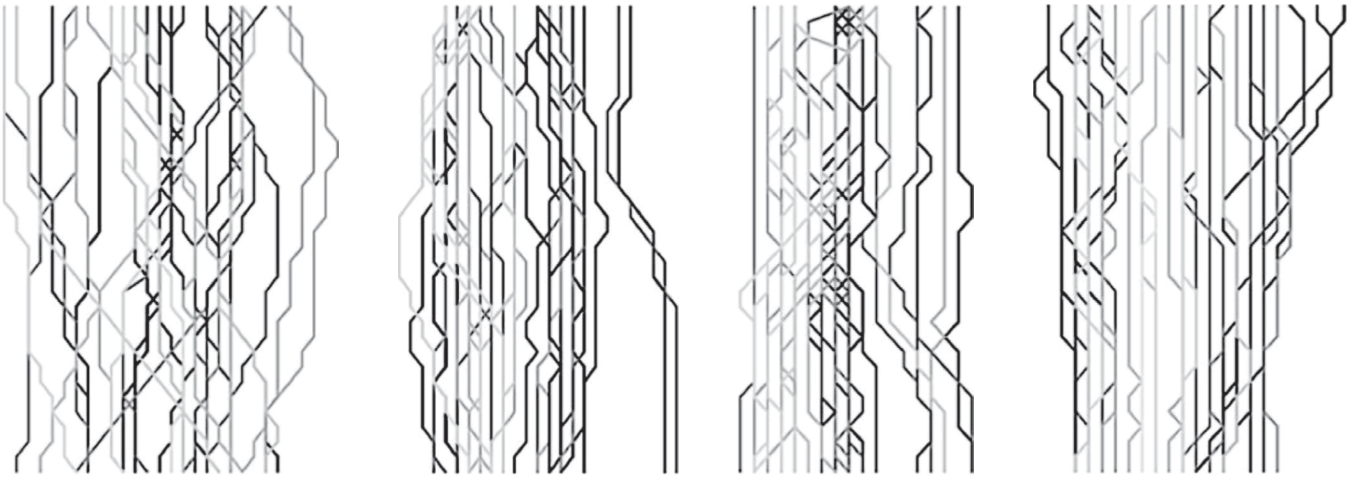



**FIGURE 3** Time distribution of observed flow rate (horizontal line denotes average LOS B). Minute 00:01:00 on the *x*-axis marks the start of observation time (2:50 p.m.).



(a) (b) (c) (d)

FIGURE 4 Trajectories of sampled pedestrians: (*a*) singles, (*b*) dyads, (*c*) triads, and (*d*) groups of four.

singles, dyads, triads, and groups of four. Data averages (with standard deviations) follow:

| *Parameter* | *Singles* | *Dyads* | *Triads* | *Fours* |
|---|---|---|---|---|
| Path (m) | $13.96 \pm 1.11$ | $13.39 \pm 0.38$ | $13.34 \pm 0.27$ | $13.16 \pm 0.46$ |
| Speed (m/s) | $1.22 \pm 0.16$ | $0.92 \pm 0.18$ | $0.73 \pm 0.10$ | $0.65 \pm 0.04$ |

Differences in group proxemic patterns were not considered. Two-tailed *t*-test analyses showed a significant ($p < .05$) difference between the average path lengths of singles and groups (including dyads, triads, and groups of four). Additional two-tailed *t*-test analyses revealed a significant difference ($p < .01$) in walking speed among singles [1.22 m/s, ± 0.16 standard deviation (SD)], dyads (0.92 m/s, ± 0.18 SD), triads (0.73 m/s, ± 0.10 SD), and groups of four (0.65 m/s, ± 0.04 SD). In summary, results indicated that the average path was 4.48% longer for singles than for groups and that the average walking speed was 37.21% slower for groups than for singles.

## LABORATORY INVESTIGATION

### Objectives and Hypothesis

An experimental investigation was performed on April 19, 2012, at Monash University, Clayton Campus, in Melbourne, Victoria, Australia, to empirically study the effect of grouping on pedestrian crowd dynamics. The walking speeds of single pedestrians and groups were measured in a corridorlike setup in a laboratory setting and then compared. The authors' hypothesis was that under high-density conditions, groups walk more slowly than single pedestrians.

### Sample

A total of 68 subjects (45 males and 23 females, aged 20 to 30 years old, mostly students) participated in the experimental study. The walking speeds of a portion of the participants—15 singles and 15 persons in groups (i.e., four dyads, one triad, and one group of four)—were observed to test the hypothesis. Some participants spontaneously organized themselves into groups during the experimental procedure because they were classmates or friends. Differences in gender, group size, and group proxemic patterns were not considered.

### Experimental Design

The experiment was designed between subjects relative to the independent variable "subject alone or group member." LOS (in pedestrians/min/m) was estimated by counting the number of people passing through the end point of the experimental setting per unit of time. The walking speed of a single pedestrian or a pedestrian in a group was considered a dependent variable. Groups in the stream of passersby were identified by verbal and nonverbal communication among individuals (talking, gesticulation, visual contact, body orientation, and spatial arrangement).

### Experimental Procedure and Setting

Participants were asked to walk through the path freely at a normal speed, three times. The path comprised a gathering area (6 × 6 m), a corridor with start and end points (1.5 m wide × 12 m long), and a turning path to come back to the gathering area (Figure 5). The path was delimited with desks and white tape on the floor. Three video cameras recorded movements.

### Results

#### *Level of Service*

LOS was estimated by counting the number of people walking through a certain unit of space (m) in a certain unit of time (min) according to the *Highway Capacity Manual* (*21, 22*). Results indicated an average of LOS E (74.18 pedestrians/min/m, ±1.85 SD), which is associated with irregular flow under high-density conditions, typically observed in pedestrian crowd dynamics.

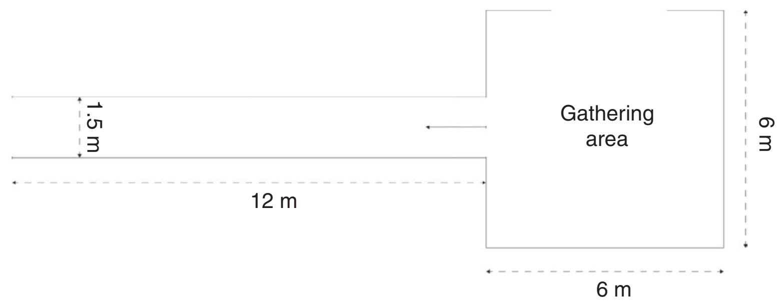



**FIGURE 5 Schema of experimental setting (not to scale) illustrates gathering area, corridor scenario, and turning path to return to gathering area.**

### *Walking Speed*

Two-tailed *t*-test analyses were performed to identify differences between the average walking speeds of singles (1.00 m/s, ±0.07 SD) and groups (0.89 m/s, ±0.01 SD). Results indicate that the walking speed of a group is slower than that of a single pedestrian ($p < .01$). Despite the narrow width of the path, the observed pedestrian dynamics were characterized by continuous overtaking maneuvers (singles) and waiting maneuvers (members of a group wishing to maintain spatial cohesion and proxemic arrangements while walking). In summary, results indicate that under high-density conditions, the average walking speed of a group is 11% slower than that of a single pedestrian. Therefore, the authors' hypothesis is valid.

## FINAL REMARKS

Recent crowd disasters have highlighted the importance of properly managing large urban events and public spaces to enhance the safety of people in a crowd during evacuation, under both normal and emergency conditions. Previous studies reported that one of the most important factors to consider in studying pedestrian crowd dynamics is the effect of grouping (e.g., of families or friends) on the overall phenomenon (*10, 11*); however, a lack of empirical data inhibits the development and testing of models specifically focused on such scenarios. A combined empirical investigation that focused on the effect of grouping on pedestrian crowd dynamics was conducted both in the field and in a laboratory setting to address that gap. The empirical contributions are reported more comprehensively elsewhere (*23, 24*).

The effect of the proxemic behavior or spatial arrangement of walking groups (characterized by the need to maintain cohesion among individuals to facilitate social interactions and communication) on normal and orderly egress processes was investigated under variable-density conditions by applying the general framework of proxemics. Observation of bidirectional pedestrian flows in an urban scenario indicated that the 84% of the pedestrian crowd was composed of groups. Under the low- to medium-density conditions (LOS B) observed, the walking speed of groups (dyads, triads, or groups of four) was 37% lower than that of single pedestrians (Figure 6). Experimental results from pedestrian flows observed in a laboratory setting (a corridorlike scenario) confirmed the effect of groups on crowd dynamics, showing that under high-density conditions (LOS E), the walking speed of groups (dyads, triads, or groups of four) was 11% lower than that of singles (Figure 6).

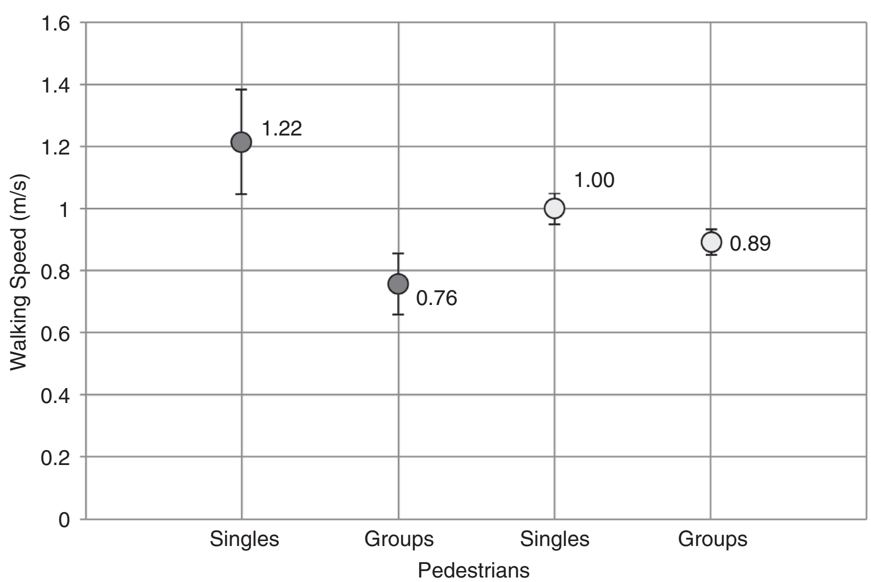



**FIGURE 6 Average walking speeds (with standard deviations) of singles and groups, from in-field observation results (LOS B = ●) and experimental laboratory results (LOS E = ○).**

The walking speed results of in-field observations and the experimental study in a laboratory setting showed significant differences between single pedestrians and groups. A comparison of results indicates that the average walking speed of singles and groups observed in the urban scenario are characterized by a larger variability than results of the experimental study (Figure 6). Moreover, the walking speeds of groups were lower under LOS B (in-field observation) than under LOS E (experimental investigation). This difference stems from the greater complexity of the observed walkway (large-scale scenario, bidirectional flows, irregular flows under low- to medium-density conditions, heterogeneous sample, and group dynamics in a natural setting characterized by leisure and sightseeing) compared with the laboratory setting (corridorlike scenario, unidirectional flows, irregular flows under high-density conditions, homogeneous sample, and absence of distracting environmental stimuli). The analysis of the overall spatial interactions indicated that single pedestrians crossed the space with frequent changes of direction to maintain velocity and avoid perceived obstacles (e.g., slower pedestrians or groups). In contrast, group behavior was more stable overall, adjusting spatial arrangements to the contextual conditions of irregular flow, with overtaking and waiting dynamics among individuals in a group when faced with an oncoming pedestrian. In conclusion, the proxemic behavior of walking groups has a negative effect on walking speed because individuals must maneuver continuously to maintain spatial cohesion and preserve the ability to communicate.

The achieved results demonstrate the necessity of taking into account the presence of groups in the crowd and the effect of their spatial interactions when estimating the time required for crowd egress under both normal and emergency conditions. Additional empirical studies of group behavior in various circumstances (e.g., in-field observations and experimental investigations of crossing and merging streams of pedestrians under high-density conditions) could provide significant benefits and contribute to the development of computational models of crowd dynamics for complex environments. The final aim of this study is to support the development of applicative strategies and solutions for enhancing the safety of pedestrians in mass gatherings and public infrastructures.

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*In-field observations at the Galleria Vittorio Emanuele II were carried out with authorization from the municipality of Milan and in compliance with Italian legislation about the privacy and anonymity of people recorded in the pedestrian flows. The experimental study presented in this paper was performed with the authorization of the ethics committee of Monash University.*

*The Traffic Flow Theory and Characteristics Committee peer-reviewed this paper.*

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