Crossing Disciplinary Borders Through Studying Walkability

Stefania Bandini[1,2], Andrea Gorrini[1(✉)], and Katsuhiro Nishinari[2]

[1] Department of Informatics, Systems and Communication, CSAI-Complex Systems and Artificial Intelligence Research Center, University of Milano-Bicocca, Viale Sarca 336 - Edificio U14, 20126 Milano, Italy
stefania.bandini@disco.unimib.it, andrea.gorrini@unimib.it

[2] RCAST-Research Center for Advance Science and Technology, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan
tknishi@mail.ecc.u-tokyo.ac.jp

Abstract. Computer-based simulations of pedestrian dynamics are aimed at improving the walkability of urban crowded scenarios, considering the pedestrians' comfort and safety. The validation of the developed models requires a cross-disciplinary approach, and the acquisition of empirical evidences about human behavior is mandatory. The main purpose of this work is to report two case studies which allowed to perform simulations and validate the `ELIAS38` agent-based computational model: (*i*) the naturalistic observation of pedestrian dynamics in an urban commercial-touristic walkway, focused on the impact of grouping and ageing on speed; (*ii*) the controlled experiment of pedestrian spatial behavior, focused on the impact of speed and cultural differences on personal space.

Keywords: Pedestrian · Walkability · Groups · Age · Culture · Proxemics

1 Introduction

Progressive urbanization is a global tendency and it is estimated that by 2025 the 58 % of the world population will live in large urban agglomerates [17]. Many cities around the world are developing advanced and integrated solutions comprising sustainable mobility strategies to meet the citizens' needs and to increase their quality of life [25]. Facing this trend, advanced urban planning activities are shifting toward a focus on *walkability*, namely how conducive and friendly the urban environment is for walking (e.g., quality of sidewalks, route navigation, pedestrian-vehicular interaction) [1]. Moreover, the European Charter of Pedestrians' Rights[1] (1988) highlighted the need to ensure the comfort and safety of pedestrians in urban areas, including the elderlies and people with impaired mobility (i.e. *pedestrian-friendly cities*).

[1] http://goo.gl/7J8xij.

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The evaluation of the walkability degree of urban areas requires the involvement of many actors, skills, and disciplines, in a global scenario: the strategic and practical solutions which will emerge will be not just a mere sum of pieces of knowledge, and only cross-disciplinary attitudes in the creation of innovative approaches will increase the possibility to succeed for the future of our style of life in the cities (e.g., urban planning, traffic engineering, health science, social science, computer science).

Within this scenario, the role of advanced computer-based systems for the simulation of the dynamical behavior of pedestrians [11] is becoming a consolidated and successful field of research and application, thanks to the possibility to test the efficacy of alternative spatial layouts focusing on pedestrian dynamics and walkability assessment. The development of validated and realistic simulation systems also requires a cross-disciplinary approach, involving not only heterogeneous knowledge to be incorporated in the computational models, but also diverse methodological approaches to collect, validate and test the model itself and the related simulation results in order to support at best decision makers and planners.

The main purpose of this paper is to introduce some results of a cross-disciplinary methodological framework aimed at collecting empirical data about human locomotion and spatial behavior through naturalistic observations (*in vivo*), controlled experiments (*in vitro*) and agent-based simulations (*in silico*). This methodological framework contributes to the study of walkability through the theoretical definition and the empirical study of three main factors which drive pedestrian behavior in terms of speed profiles and stress-response to density in urban crowded scenarios: group-driven, age-driven and cultural-driven pedestrian behavior.

Section 2 briefly introduces such factors as distinctive of the proposed approach, while the proposed methodology is presented in Sect. 3, with reference to the design and execution of naturalistic observations and controlled experiments, providing data to feed the agent-based simulation system `ELIAS38` [2]. Case studies are presented in Sect. 4, focusing on the empirical investigation of the impact of grouping, ageing and cross-cultural differences on pedestrian locomotion and spatial behavior. Final remarks about results and their employment for assessing the quality of simulation results (heterogenous group and age-driven speed profiles), as well as ongoing works about the assessment of walkability in urban critical scenarios are presented in Sect. 5.

2 Modeling Group, Age and Cultural-Driven Pedestrian Behavior

The development of computer-based models and systems to simulate the dynamical behavior of crowds and pedestrians is challenged in facing three main factors characterizing the reality of the collective walking: groups, age and culture. Speed profiles and stress-response to density in urban crowded scenarios highly depend on these factors, contributing to the definition of assessment issues for walkability.

- **Group-driven pedestrian behavior**: recent empirical contributions [13,22] clearly showed that pedestrian flows in urban crowded scenarios are characterized by the preponderant presence of groups, with the prevalence of *dyads* in the related granulometric distribution. This phenomenon is largely determined by the motivation by which people are gathered or move through a certain environment, and/or by the type of event they are participating to [6]. For example, train stations are mainly characterized by the presence of fast moving single commuters, while other collective venues are more often characterized by the presence of informal and/or structured groups of visitors, generally moving slower than the former type of pedestrian. Analyses of pedestrian dynamics not considering the impact of groups have a reduced accuracy, since grouping was found to negatively impact flow rate, speed and evacuation time [30]. This is due to the difficulty of group members in coordinating their movement depending on (*i*) the environmental level of density [7,21], (*ii*) the need to maintain spatial cohesion to communicate while walking (i.e. *proxemic behavior*) [15] and (*iii*) the urgency to evacuate together in case of emergency (i.e. *affiliative behavior*) [20].
- **Age-driven pedestrian behavior**: the notion of *Age-friendly Cities*, introduced by the World Health Organization [24], offers a framework for the development of urban contexts encouraging inclusion and active ageing of the citizens. It contains guidelines and policies for assess and increase the accessibility of urban facilities and services for the elderly. Moreover, the mobility of aged people is a key factor for maintaining an active and productive status, in spite of the progressive decline of cognitive and locomotion skills linked to ageing [27]. Compared to adult pedestrians, elderlies are characterized by lower speed and larger interpersonal distances while walking. This is strongly conditioned by the progressive decline in the operation of (*i*) perceptive sensors (e.g. limited perception of light and colors) and (*ii*) locomotor-cognitive skills (e.g., reduced range of motion, loss of muscle strength and coordination, changes in posture, diminished attention and reaction time, spatial disorientation) [31]. All these bodily changes lead to a subjective perception of physical vulnerability and a sense of fragility at the psychological level [32]. This is the reason why aged people are more provident in the space, and they move more slowly keeping more space around themselves.
- **Culture-driven pedestrian behavior**: social and spatial interactions of pedestrians in urban crowded scenarios depend on several socio-psychological factors related to the variability among subjects' culture (i.e. *crowd profiling*) [6]. In particular, cross-cultural differences has an impact on human response to the physical condition of density by itself. The need of optimal reciprocal distances with other people is driven by psychological factors and social norms related to the notion of *personal space* [16]: the area immediately surrounding individuals, into which strangers cannot intrude without arousing discomfort and stress (i.e. *crowding*) [4]. In high-contact cultures (e.g., the Mediterranean, Arabic, Hispanic cultures) people exhibit closer distances compared to no-contact cultures (e.g., Northern European, Caucasian American cultures) [15]. The Japanese culture is characterized by a scarce acceptance for

spatial proximity during face to face social interaction, but an high tolerance for spatial intrusion in situation of high density in public spaces [19]. Lastly, the intensity of sensory inputs and physical contact in high density situations can be labeled either positively or negatively, depending on contexts of social interaction [26].

3 Methodological Framework

As previously mentioned, providing methodological and technological supports to decision makers through new generations of simulation systems for walkability assessment means providing realistic models and accurate data collection. The here proposed approach is based on the integration of data collection methodologies from social sciences through naturalistic observations and experiments of pedestrians' behavior (i.e. *analysis*), and the related activity of agent-based modeling and simulation of pedestrians dynamics (i.e. *synthesis*) [3].

3.1 In Vivo Observation

Unobtrusive naturalistic observations, *in vivo* (from Latin, living), allow to collect empirical data about pedestrians' behavior, considering the physical and social features of the environment in which the subjects are situated (subjects are not aware to be observed, the observer does not intrude the stage) [10]. This method is characterized by the possibility to exert a limited amount of control over the environment, but by an higher possibility to generalize results (i.e. *external validity*) [12].

Design and perform naturalistic observations in urban scenarios requires to systematically consider several practical elements (e.g., features of the scenario, duration time, staff members, equipment for data collection, authorization, ethical restrictions). In particular, the issue about the privacy of the people participating the study represents a crucial aspect, due to the difficulty to obtain their informed consent beforehand [33].

The information collected during the survey (e.g., notes, video footages) are analyzed by using quantitate techniques and statistics, focused on the occurrence and modalities of specific behavioral indicators (e.g., level of density, trajectories, speed, grouping, pedestrian profiling, habits). It is also highly recommended to cross-check results by means of two or more observers, who analyze data by using a shared taxonomy for the definition of the observed phenomenon.

3.2 In Vitro Experiment

Controlled experiments, *in vitro* (test tube), allow to systematically measure the impact of a manipulated stimulus event (i.e. *independent variable*) on pedestrians' behavior (e.g., crowding stress reaction to density, speed, spatial behavior) [10]. Contrary to naturalistic observations, experiments are performed in laboratory settings in order to exert the maximum amount of control over the environment (i.e. *internal validity*). The most critical aspect is the limited possibility to extend the results achieved in an artificial setting to natural contexts, considering also that the merely presence of the experimenter has an impact on subjects' behavior in terms of performance and social interaction (i.e. *Hawthorne effect*) [10].

Experiments are aimed at verifying the validity of a priori hypotheses by means of standard and replicable procedures, typically following the protocol of clinical trials [12]: participants are randomly assigned to the treatment condition or control condition (no treatment), in order to compare results (i.e. *between subjects*). Alternatively, all participants are assigned to the treatment condition, in order to compare results among pre-test and post-test measurements (i.e. *within subjects*). Since experiments on human behavior potentially includes stressful or harmful factors related to the procedure by itself, it is required to obtain the authorization of the ethic committee of the institution that promotes the survey and the informed consent of participants [33].

3.3 In Silico Simulation

Although there are some objections about the simplified level of correspondence between computer-based simulations and complex social systems [11], this methodology, *in silico* (on the computer) allows to envision those phenomena that are difficult to be directly observed in real scenarios, testing alternative conditions and courses of action (i.e. *what-if scenarios*). The issue of defining formal computational models about pedestrian dynamics has been tackled from different perspectives:

- *Physical* approach [18] represents pedestrians as particles subject to forces (e.g., attraction and repulsive forces), in analogy with fluid dynamics;
- *Cellular Automata* approach [23] represents pedestrians as occupied states of the cells. Pedestrian interactions are based on the *floor field* method: a virtual traces that influence pedestrian transitions and movements;
- *Agent-based* approach [8] represents pedestrians as heterogeneous, autonomous and situated entities moving according to behavioral rules and specifications.

`ELIAS38` (the name is in memory of Elias Canetti [5] who studied the behavior of crowd for thirty-eight years) is an agent-based simulation systems whose core computational model allows the explicit representation of groups of agents, interacting through proxemics rules [2,3]. Agents are characterized by (*i*) perceptive and behavioral specifications (e.g., perceive and avoid obstacles, follow paths, perceive other agents) and the (*ii*) capability to communicate in order to achieve some individual or shared goals (e.g., every group is driven by the tendency to maintain spatial cohesion during locomotion). Data coming from the quantitative analysis of *in vivo* and *in vitro* studies allow the calibration and the validation of the simulation tool, in order to apply analytical tools (e.g., Fruin's Walkway Level of Service Criteria (LOS) metrics [9]) on what-if sessions at different conditions. Within this computational framework, it is possible to perform walkability assessments in terms of the above-mentioned speed profiles and stress-response to density in presence of groups, heterogeneous ages and cultural proxemics specifications.

4 Case Studies

This Section presents two empirical studies based on (*i*) the observation of small size group behavior (i.e. *dyads*) walking in situation of irregular density, considering also the impact of age, (*ii*) the experimental investigation of personal space in dynamics setting.

4.1 Observation of Pedestrian Circulation Dynamics

The survey was performed on November 24th 2012, and it consisted of the unobtrusive video-recorded observation of pedestrian circulation dynamics at the Vittorio Emanuele II gallery (Milan, Italy). The gallery is a popular touristic-commercial walkway, exclusively intended for pedestrians and characterized by heterogeneous pedestrian profiles (tourists, shoppers, strollers and inhabitants) and group granulometric distribution [13].

Data analysis was focused on estimating the environmental level of density and the speed of a sample of singletons and dyads composed of adult and elderly pedestrians. The detection of dyads and elderly pedestrians (approximately 70 y.o.) was supported by an *ad hoc* designed checklist, comprising a set of locomotion, communication and physical indicators. No.62 pedestrians were tracked by using the open source software *Tracker Video Analysis and Modelling Tool* (www.cabrillo.edu).

Level of Density. The average level of density was 0.22 people/squared meter. The average flow rate was 7.78 pedestrian/minute/meter. Results (see Fig. 1) were compared according to the Walkway Level of Service Criteria (LOS) [9]: a range of values that standardly describe the impact of contextual situations of density on pedestrian circulation dynamics (from LOS A-pedestrian free flow, to LOS F-extremely difficulty in walking movements). The average level of density and flow rate corresponded to LOS B, that is associated with minor conflicts under low-medium density condition.

Speed and Trajectories. The sample[2] was composed of: 15 adult singles (AS), 16 adult dyad members (AD), 15 elderly singles (ES), 16 elderly dyad members (ED). Results about speed and trajectories are presented in Fig. 2 and Table 1.

[2] 60 % single males and 40 % single females. 25 % male-male dyads, 25 % female-female dyads, 50 % mixed gender. 58 % pedestrians from South to North, 42 % from North to South. Pedestrians who stopped were not tracked, as well as mixed age dyads.

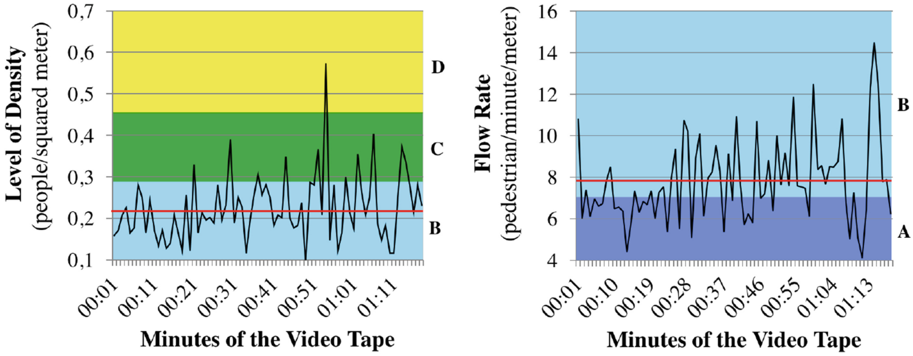

Fig. 1. Results about level of density, flow rate and LOS.

A two-factor analysis of variance[3] showed a significant main effect for the *group* factor on speed [F(1,58) = 28.61, $p < 0.0001$], and a significant main effect for the *age* factor on speed [F(1,58) = 105.97, $p < 0.0001$]. Finally, results showed that the interaction between the *group* and *age* factors on speed was significant [F(1,58) = 13.58, $p < 0.001$]. A series of independent-samples t-tests showed a significant difference between the speed of: AS and AD, t(29) = 2.05, $p < 0.0001$; AS and ES, t(28) = 2.05, $p < 0.0001$; AS and ED, t(29) = 2.05, $p < 0.0001$; AD and ES, t(29) = 2.05, $p < 0.001$; AD and ED t(30) = 2.04, $p < 0.0001$. There was not a significant difference between the walking speed of ES and ED, t(29) = 2.05, p = 0.21.

Results showed that at LOS B dyads walked 30 % slower than singles, and that elderly walked 40 % slower than adults. Further analysis showed that pedestrians' trajectories, gender and direction of movements had no significant effect on speed.

4.2 Experiment of Pedestrian Personal Space

The experiment was performed on June 8th 2013, at Research Center for Advance Science and Technology-RCAST of The University of Tokyo (Japan) [14]. It was aimed at measuring personal space in static and dynamic settings, taking into account the impact of speed and cross-cultural differences. In particular, the front zone of pedestrian personal space was assumed to be larger than the one in static settings and linearly speed-dependent. This is due to the need of an additional margin projected towards the direction of movement to anticipate the spatial intrusion of oncoming pedestrians.

The sample was composed of No.20 male subjects (from 18 to 25 y.o., with sufficient visual capacity, 17 Japanese, 2 Vietnamese and 1 Chinese). The subject's *state of movement* and *speed* were defined as independent variables. The size of personal space was deduced from the effects of discomfort caused by

[3] All statistics hereby presented were conducted at the p <.01 level.

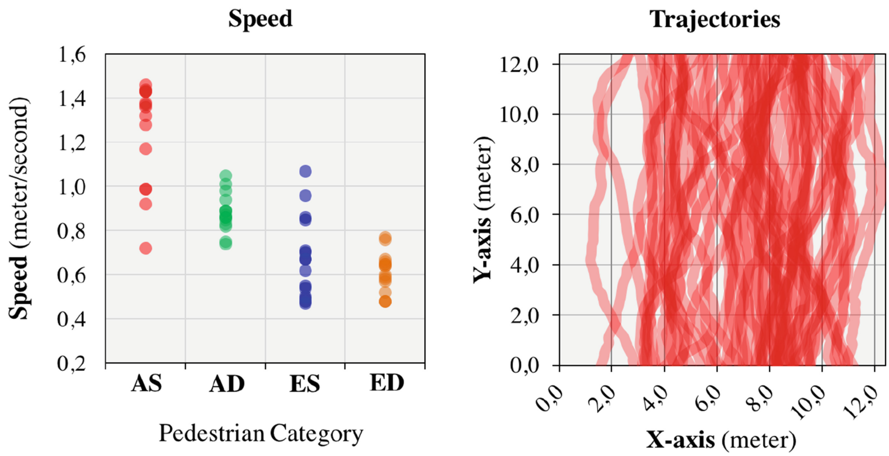

Fig. 2. Results about speed and trajectories.

Table 1. Results about speed and trajectories.

	Adult singles	Adult dyads	Elderly singles	Elderly dyads
Speed	1.25 m/s ± 0.23	0.88 m/s ± 0.08	0.68 m/s ± 0.19	0.61 m/s ± 0.09
Trajectories	13.01 m ± 0.56	12.86 m ± 0.49	12.80 m ± 0.34	12.84 m ± 0.34

spatial invasion. The experiments comprised three procedures performed within subjects (see Fig. 3):

(A) Stop-distance procedure (static setting): participant had to stop the approach of the confederate (who walked straight from a distance of 5 m), when he felt uncomfortable about spatial nearness; the distance between them was measured as the size of the front zone of participant's personal space;
(B) Approach-distance procedure (dynamic setting): participant walked towards the stationary confederate and stopped the approach when he felt uncomfortable;
(C) Locomotion-distance procedure (dynamic setting): participants walked towards the oncoming confederate and stopped the approach when he felt uncomfortable (the confederate had to stop immediately after).

Each procedure was repeated three times according to the modalities of the variable *speed* (low, medium, high speed). Participants were asked to walk following foot markers drawn on the floor, and to synchronize their gait to digital-metronome background sounds: low speed (70 bpm, 0.93 m/s), medium speed (90 bpm, 1.23 m/s), high speed (110 bpm, 1.46 m/s). Results are presented in Fig. 4 and Table 2.

Fig. 3. The experimental procedures (participant is highlighted with red color). (Color figure online)

Table 2. Results about personal space among the different procedures.

Speed	0.93 m/s	1.23 m/s	1.46 m/s
(A) Stop-distance	72.15 cm ± 25.71	94.40 cm ± 22.12	96.00 cm ± 29.16
(B) Approach-distance	70.10 cm ± 22.96	71.70 cm ± 20.29	68.45 cm ± 23.09
(C) Locomotion-distance	71.45 cm ± 21.78	68.90 cm ± 24.02	91.10 cm ± 30.30
A/B/C Procedures	71.23 cm ± 23.16	78.33 cm ± 24.25	85.18 cm ± 30.01

Stop-Distance. A one-factor analysis of variance showed a significant effect for the *speed* factor on subjects' personal space when approached by the confederate [$F(1,57) = 5.32$, $p < 0.01$]. A series of two-tails paired-samples t-tests showed a significant difference between the size of personal space at low and medium speed approach, $t(19) = 2.86$, $p < 0.01$; low and high speed approach, $t(19) = 2.86$, $p < 0.001$. There was not a significant difference comparing medium and high speed approach, $t(19) = 2.86$, $p = 0.79$. In conclusion, results showed that the size of the front zone of subjects' personal space in static settings is affected by walking speed of the approaching confederate.

Approach-Distance. A one-factor analysis of variance showed no significant effect for the *speed* factor on subjects' personal space when approaching the static confederate [$F(1,57) = 4.99$, $p = 0.89$]. A series of two-tails paired-samples t-tests showed no significant difference between results and the size of personal space in static setting (stop-distance procedure at low speed). In conclusion, results showed that the size of the front zone of subjects' personal space when moving towards a stationary person is not affected by speed, and it is similar to personal space in static situations.

Locomotion-Distance. A one-factor analysis of variance showed a slight significant effect for the *speed* factor on subjects' personal space when approaching the oncoming confederate [$F(1,57) = 4.99$, $p = 0.0154$]. A series of two-tails paired-samples t-tests showed a slight significant difference between the size of personal space at low and high speed reciprocal approach, $t(19) = 2.86$, $p = 0.011$; medium and high speed approach, $t(19) = 2.86$, $p < 0.01$. There was not a significant difference comparing low and medium speed reciprocal approach, $t(19) = 2.86$, $p = 0.60$. A two-tails paired-samples t-test showed a slight significant difference between personal space in dynamic setting (high speed reciprocal

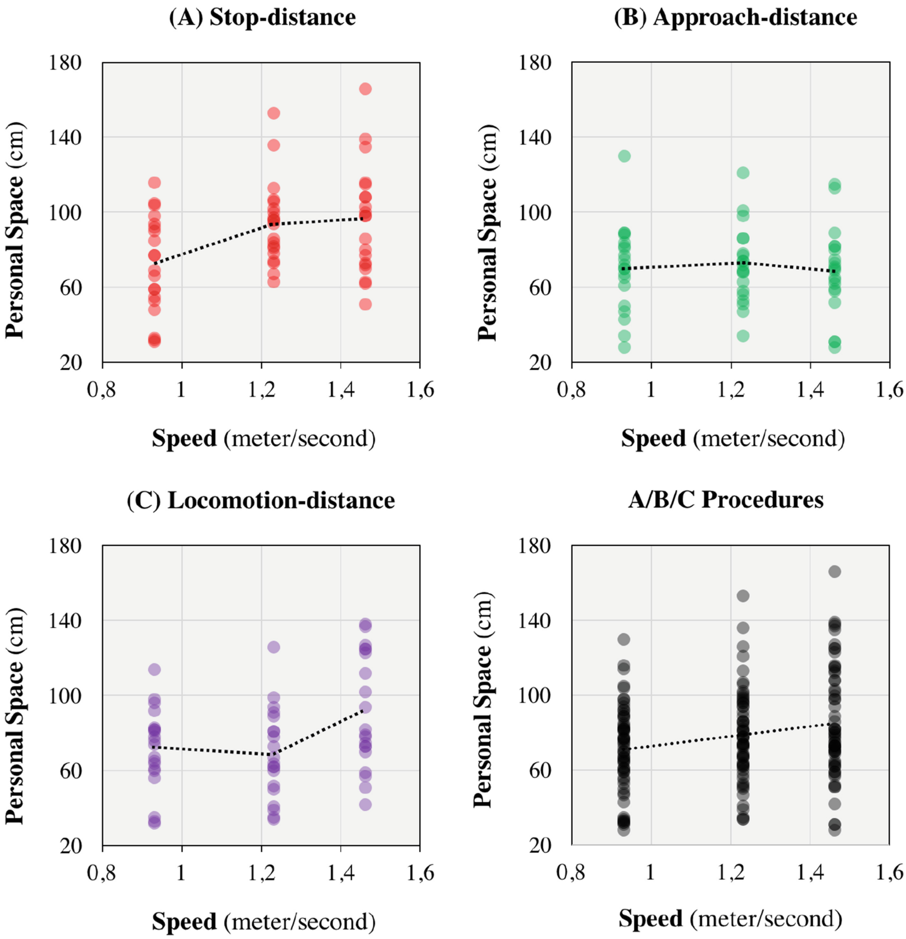

Fig. 4. Results about personal space among the different procedures.

approach) and personal space in static setting (stop-distance procedure at low speed), $t(19) = 2.86$, $p < 0.05$. In conclusion, results showed that the size of the front zone of subjects' personal space when approaching the oncoming confederate is affected by speed and that it is larger than the one in static settings.

Comparing the Impact of Speed. A linear regression was conducted to test the effect of speed on personal space among A, B and C procedures, which was significant [$F(1,179) = 8.62$, $p < 0.01$]. Results demonstrated that the size of the front zone of personal space is linearly speed-dependent, considering both static and dynamic settings.

5 Final Remarks

The current work has proposed a cross-disciplinary methodology for studying pedestrian locomotion and spatial behavior by means of empirical investigations and pedestrian computer-based simulations to support walkability assessments. The first case study was aimed at testing the impact of grouping and ageing on pedestrian behavior in an urban crowded scenario. Results showed that in situation of irregular flows age significantly reduced the speed due to locomotion skills decrease, and that dyads walked much slower than singles due to the need to maintain spatial cohesion to communicate.

The second case study was based on the experimental investigation of pedestrian personal space, taking into account the impact of speed and cross-cultural differences. Results showed that the front zone of pedestrian personal space is larger then the one in static settings (low speed approach), and that its size is linear speed-dependent. Considering the socio-demographic characteristics of participants (almost Japanese male students), results confirmed that static personal space in Japanese culture is larger than Caucasian-American culture [16].

According to the proposed methodological approach (see Sect. 3), a simulation campaign was executed to test the efficacy of the computational model incorporated in `ELIAS38` in representing group-driven heterogenous speed profiles at irregular condition of density, comparing results with the gathered empirical data [2]. Results showed that the model is consistent with the collected empirical data, representing a promising step for the improvement of the tool. In particular, the model has been able to reproduce results similar to single pedestrians' speed, but it showed a decrease in the velocity of group members lower than the observed one. However, the achieved results must be evaluated considering the adopted model configuration: all the agents have the same desired speed (1.30 m/s). This is based on the empirically observed velocity of pedestrians traveling for business purpose in an airport terminal [28], which is different from the leisure scenario observed at the gallery.

At this stage, the software has been already employed towards the simulation of real case scenarios, supporting the design of practical solutions for managing pedestrian circulation dynamics in urban contexts (e.g., designing the spatial layout of organized queue areas and access ramps in public transport stations).

In conclusion, the presented cross-disciplinary approach could be of notable interest for those attempting to properly plan and design the spatial layout of urban environments to enhance pedestrian mobility and walkability. On-going works are aimed at: (*i*) calibrating agents' speed according to the features of different simulated scenarios, as well as age-driven desired speed [29]; (*ii*) defining a proximity-based measure of density relying on the notion of pedestrian personal space and collision avoidance dynamics; (*iii*) assessing the walkability of a critical area in the city of Milan, characterized by the massive presence of elderly inhabitants and pedestrian-car risky interactions.

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References

1. Abley, S.: Walkability scoping paper. Charted Traffic Transp. Eng. **4**, 2011 (2005)
2. Bandini, S., Crociani, L., Gorrini, A., Vizzari, G.: An agent-based model of pedestrian dynamics considering groups: a real world case study. In: 2014 IEEE 17th International Conference on Intelligent Transportation Systems (ITSC), pp. 572–577. IEEE (2014)
3. Bandini, S., Gorrini, A., Vizzari, G.: Towards an integrated approach to crowd analysis and crowd synthesis: a case study and first results. Pattern Recogn. Lett. **44**, 16–29 (2014)
4. Baum, A., Paulus, P.: Crowding. In: Stokols, D., Altman, I. (eds.) Handbook of Environmental Psychology, pp. 533–570. Wiley, New York (1987)
5. Canetti, E.: Crowds and Power: Masse und Macht. Viking Press, New York (1962)
6. Challenger, W., Clegg, W., Robinson, A.: Understanding Crowd Behaviours: Guidance and Lessons Identified. UK Cabinet Office, London (2009)
7. Costa, M.: Interpersonal distances in group walking. J. Nonverbal Behav. **34**(1), 15–26 (2010)
8. Ferber, J.: Multi-agent Systems: An Introduction to Distributed Artificial Intelligence. Addison-Wesley Reading, Boston (1999)
9. Fruin, J.J.: Pedestrian Planning and Design. Metropolitan Association of Urban Designers and Environmental Planners, New York (1971)
10. Gifford, R.: Research Methods for Environmental Psychology. Wiley Blackwell & Sons, Oxford (2016)
11. Gilbert, N., Troitzsch, K.G.: Simulation for the Social Scientist. McGraw-Hill, London (2005)
12. Goodwin, C.J.: Research in Psychology: Methods and Design. Wiley, New Jersey (2009)
13. Gorrini, A., Bandini, S., Vizzari, G.: Empirical investigation on pedestrian crowd dynamics and grouping. In: Chraibi, M., Boltes, M., Schadschneider, A., Seyfried, A. (eds.) Traffic and Granular Flow'13, pp. 83–91. Springer, Switzerland (2015)
14. Gorrini, A., Shimura, K., Bandini, S., Ohtsuka, K., Nishinari, K.: Experimental investigation of pedestrian personal space: toward modeling and simulation of pedestrian crowd dynamics. J. Transp. Res. B **2421**, 57–63 (2014)
15. Hall, E.: The Hidden Dimension. Doubleday, New York (1966)
16. Hayduk, L.A.: Personal space: where we now stand? Psychol. Bull. **94**(2), 293–335 (1983)
17. Heilig, G.K.: World urbanization prospects: the 2011 revision. United Nations, Department of Economic and Social Affairs (DESA), Population Division, Population Estimates and Projections Section, New York (2012)
18. Helbing, D.: Traffic and related self-driven many-particle systems. Rev. Mod. Phys. **73**(4), 1067 (2001)
19. Iwata, O.: Crowding and behavior in japanese public spaces: some observations and speculations. Soc. Behav. Pers. Int. J. **20**(1), 57–70 (1992)
20. Mawson, A.R.: Mass panic and social attachment: the dynamics of human behavior. Ashgate Publishing Company, Burlington (2007)

21. Moussaïd, M., Perozo, N., Garnier, S., Helbing, D., Theraulaz, G.: The walking behaviour of pedestrian social groups and its impact on crowd dynamics. PloS ONE **5**(4), e10047 (2010)
22. Musso, A., Nuzzolo, A., Crisalli, U., Longo, G.: Transportation Research Procedia, vol. 5. Elsevier, Japan (2015)
23. Nishinari, K., Kirchner, A., Namazi, A., Schadschneider, A.: Extended floor field CA model for evacuation dynamics. IEICE Trans. Inf. Syst. **87**(3), 726–732 (2004)
24. World Health Organization: Global age-friendly cities: a guide. World Health Organization (2007)
25. World Health Organization, et al.: Pedestrian safety: a road safety manual for decision-makers and practitioners. World Health Organization (2013)
26. Patterson, M.L.: An arousal model of interpersonal intimacy. Psychol. Rev. **83**(3), 235–45 (1976)
27. Schaie, K.W., Willis, S.L.: Handbook of the Psychology of Aging. Academic Press, New York (2010)
28. Schultz, M., Schulz, C., Fricke, H.: Passenger dynamics at airport terminal environment. In: Rogsch, C., Klingsch, W., Schadschneider, A. (eds.) Pedestrian and Evacuation Dynamics 2008, pp. 381–396. Springer, Heidelberg (2010)
29. Shimura, K., Ohtsuka, K., Vizzari, G., Nishinari, K., Bandini, S.: Mobility analysis of the aged pedestrians by experiment and simulation. Pattern Recogn. Lett. **44**, 58–63 (2014)
30. Templeton, A., Drury, J., Philippides, A.: From mindless masses to small groups: conceptualizing collective behavior in crowd modeling. Rev. Gen. Psychol. **19**, 215–229 (2015)
31. Webb, J.D., Weber, M.J.: Influence of sensory abilities on the interpersonal distance of the elderly. Environ. Behav. **35**(5), 695–711 (2003)
32. Winogrond, I.R.: A comparison of interpersonal distancing behavior in young and elderly adults. Int. J. Aging Hum. Dev. **13**(1), 53–60 (1981)
33. World Medical Association. World medical association declaration of helsinki: ethical principles for medical research involving human subjects. Int. J. Bioeth., **15**(1), 124 (2004)