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EMPIRICAL STUDIES AND COMPUTATIONAL RESULTS OF A PROXEMIC-BASED MODEL OF PEDESTRIAN CROWD DYNAMICS

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Ph.D. Thesis

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1 Introduction

The investigation of pedestrian crowd dynamics is a complex field of study, that requires knowledge from an interdisciplinary approach considering the variety of relevant skills (e.g., social science, computer science, traffic engineering, applied mathematics, urban planning). In particular, the use of computer-based simulations is a consolidated and successful domain, thanks to its scientific relevance and its capability to provide applicative solutions for supporting both public and private institutions in managing urban crowded events (e.g., trade exhibition, political gathering) and mass gathering-transit facilities (e.g., theater, train station).

In order to finalize simulations into decisions and operational steps it is necessary to validate computational models by using empirical evidences, focused on both individual and aggregate levels of investigation. At this stage, the social science contribution plays a crucial role for the study of human locomotion behavior in crowded environments. In this respect, the thesis work is based on different methodologies for data collection: unobtrusive on-field observations and controlled experimental investigations in laboratory setting. This is aimed at defining descriptive sets of metrics and parameters for characterizing pedestrian crowd dynamics and support the validation of computational models, both in terms of expressiveness and efficiency.

The early interest in studying crowd dynamics started in the late 19th century, thanks to the french psychologist Gustave Le Bon (1897), who was inspired by the growing urbanization and the need to manage public order in case of mass demonstrations, riots and revolutions. Far from the Le Bon's definition of crowds, the Emergent Norm Theory (Turner and Killian, 1987) and the Elaborated Social Identity Model (Reicher, 2001) more recently proposed a social normative interpretation of crowd behavior, even in emergency situations. Despite this body of literature, the definition of the phenomenon is still controversial, due to the lack of standard guidances for data collection.

For this reason, the thesis work is aimed at analytically studying pedestrian crowd dynamics by means of the application of the general framework of *proxemics* (i.e. human spatial behavior) (Hall, 1966), thanks to its ability to model the social relationships among people and groups as they interact. In particular, the novelty of this work consists of the extension of the proxemic theory towards the empirical investigation of human spatial behavior during locomotion in situation of variable density (considering both individual and group levels of investigatigation). In this schema, we focused on the impact of (*i*) proxemics (e.g., interpersonal distances, personal space, crowding in situation of high density, group spatial arrangement), (*ii*) grouping and (*iii*) density on pedestrian crowd dynamics, as described below:

- *proxemics*: the term proxemics was introduced by Edward T. Hall (1966) for the study of human spatial behavior, as a type of nonverbal communication that conveys information about the nature of participants' relationship outside the spoken language. We applied the general framework of proxemics to empirically investigate the dynamic regulation of interpersonal distances among pedestrians within the crowd;

- *grouping*: defined as two or more people who interact to achieve a shared goal (Turner, 1982), groups are the basic interacting elements that compose a crowd (e.g., relatives, friends). Both in normal and emergency situations, pedestrian crowd dynamics are characterized by the presence of groups, which generate patterns of movement generally respected by other pedestrians (Mawson, 2007);

- *density*: the physical features of the environment significantly impact pedestrian crowd dynamics. Due to the lower degree of freedom for spatial positioning, critical situations of high density are characterized by competitive interactions among pedestrians (Fruin, 1971) and crowding (Baum and Paulus, 1987), a physiological and psychological response of stress.

The methodological approach that sets the thesis work can be synthetically defined as a virtuous cycle composed of different practices for data collection (as illustrated in Figure 1.2): *in vivo* observation of pedestrian circulation dynamics in urban crowded scenarios, *in vitro* experimental investigation of human locomotion and spatial behavior in laboratory setting. This is aimed at validating pedestrian crowd simulations, by checking if the computational models are able to generate outcomes that are similar to the ones produced by the target. Then, *in silico* simulations can be used as virtual experimental settings, considering the possibility to investigate those situations that are difficult to be directly observed (i.e. what-if scenarios).

In conclusion, we proposed the integration between the social science approach (e.g., theoretical framework, empirical investigation) and the computer science contribution focused on modeling and simulations (see Figure 1.1). Thanks to the collaboration with the Complex Systems and Artificial Intelligence research centre of the University of Milano-Bicocca (Milan, Italy), this work was aimed at improving and validating the computational models of MAKKSim, a pedestrian crowd simulation platform. The results achieved are currently applied towards the design of applicative strategies for supporting the management of pedestrian crowd dynamics, with reference to architectural solutions for enhancing the spatial efficiency of potentially crowded facilities, both in terms of comfort and safety.

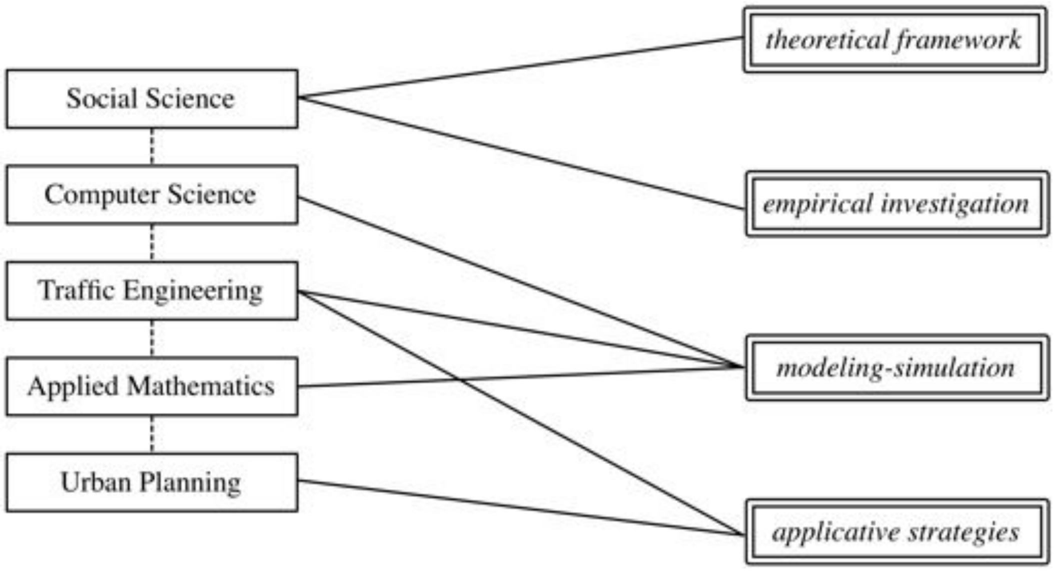

Figure 1.1: *The variety of research efforts that set the interdisciplinary investigation of pedestrian crowd dynamics (e.g., social science, computer science, traffic engineering, applied mathematics and urban planning).*

1.1 Contributions

The thesis work presents innovative contributions from different levels. The social science theories about crowd dynamics are proposed in the first part of the work, considering both ordinary and emergency situations. Then, the proxemic theory has been reviewed with respect to individual and group levels of investigation. This represents a consolidated domain of interest, but mainly focused on static situations of social interaction. The novelty of this work consists of the application of the general framework of proxemics to characterize pedestrian crowd dynamics, focusing on human locomotion and spatial behavior in situation of variable density (e.g., pedestrian personal space, walking group spatial arrangement).

The second part of the thesis presents the adopted methodological approach for the empirical investigation of pedestrian crowd dynamics, as composed of: unobtrusive observations of pedestrian circulation dynamics in urban crowded scenarios, experimental investigations of human locomotion and spatial behavior in laboratory setting, computer-based simulations of pedestrian crowd what-if scenarios. In this respect, although there are some objections about the simplified level of correspondence between simulations and real phenomena, this method represents an innovative contribution for the study of complex social systems from a different layer of abstraction (Gilbert and Troitzsch, 2005).

1.2 Thesis Overview

The work is organized in two main parts. The first includes the social science framework about crowd dynamics and proxemics and the methodological approach, while the second part consists of several empirical studies. A summary of the contents is provided as follows. Starting from the pioneering study of Gustave Le Bon (1897), the social science contributions about crowds are reviewed in Chapter 2 (e.g., Contagion-Transformation Theory, Elaborated Social Identity Model, Emergent Norm Theory). Section 2.5 is particularly focused on the Affiliative Approach and its contribution towards the definition of crowd dynamics in situations of emergency. Chapter 3 presents the proxemic theory (Section 3.2) and the notion of personal space (Section 3.3). The proxemic behavior of group members is presented in Section 3.4, considering both in static and motion situations. Chapter 4 presents the methodological approach, as composed of: in vivo observation (Section 4.2), in vitro experiments and in silico simulations (Section 7), with particular reference to the simulation platform MAKKSim.

Chapter 5 proposed the results achieved by means of two observations performed at the Campus of the University of Milano-Bicocca (Italy) (Section 5.2) and the Vittorio Emanuele II gallery (Milan, Italy) (Section 5.3). Chapter 6 presents two experiments focused on the combined impact of turning path and grouping on pedestrian crowd dynamics (Section 6.2) and the size of pedestrian personal space (Section 6.3). Chapter 7 presents a simulation campaign performed by using MAKKSim (Section 7.2). The results achieved (e.g., impact of grouping on pedestrian dynamics in situations of variable density) have been compared with the collected empirical data for sake of model validation. The thesis ends with final remarks about the achieved results and future works. In particular, further empirical studies and simulations are going to be performed, in order to improve the model of MAKKSim and support the management of pedestrian crowd dynamics.

1.3 Relevant Publications

The contents of the current thesis work were published and presented in International Journals and Conferences, as presented below:

- Bandini, S., Crociani, L., Gorrini, A., Vizzari, G. (2014). Empirical Investigation on Pedestrian Crowd Dynamics in Presence of Groups: a Real World Case Study. *13th International Conference on Autonomous Agent and Multiagent System*, Paris, France (submitted).

- Gorrini, A., Shimura S., Bandini, S., Ohtsuka, K. and Nishinari, K. (2014). An Experimental Investigation of Pedestrian Personal Space: Towards Modeling and Simulations of Pedestrian Crowd Dynamics. *Transportation Research Board 93rd Annual Meeting*, Washington DC, US (accepted).

- Gorrini, A., Bandini, S., Sarvi, M. (2014). Groups Dynamics in Pedestrian Crowds: Proxemic Behavior Estimations. *Transportation Research Board 93rd Annual Meeting*, Washington DC, US (accepted).
- Gorrini, A., Bandini, S., Vizzari, G. (2013). Empirical Investigation on Pedestrian Crowd Dynamics and Grouping. *Proceeding of the Conference of Traffic and Granular Flow 2013*, Forschungszentrum Julich, Germany (accepted).
- Bandini, S., Gorrini, A., Vizzari, G. (2013). Towards an Integrated Approach to Crowd Analysis and Crowd Synthesis: a Case Study and First Results. Journal of Pattern Recognition Letter - http://dx.doi.org/10.1016/j.patrec.2013.10.003.
- Gorrini, A., Bandini, S., Sarvi, M., Dias, C., and Shiwakoti, N. (2013). An empirical study of crowd and pedestrian dynamics: the impact of different angle paths and grouping. *Transportation Research Board, 92nd Annual Meeting*, Washington DC, US, p.42.
- Bandini, S., Gorrini, A., Manenti, L., Vizzari, G. (2012). Crowd and Pedestrian Dynamics: Empirical Investigation and Simulation. *8th International Conference on Methods and Techniques in Behavioral research - Proceedings of Measuring Behavior 2012*, Utrecht, Netherlands, 308-311.
- Federici, M.L., Gorrini, A., Manenti, L., Vizzari, G. (2012). Data Collection, Modeling and Simulation: Case Study at the University of Milan-Bicocca. *Proceedings of Workshop CCA - Forth International Workshop on Crowds and Cellular Automata at ACRI 2012 - Cellular Automata for Research and Industry*, Santorini, Greece, 699-708
- Federici, M.L., Gorrini, A., Manenti, L., Vizzari, G. (2012). An innovative scenario for pedestrian data collection: the observation of an admission test at the University of Milano-Bicocca, *6th International Conference on Pedestrian and Evacuation Dynamics - PED 2012*, Zurich, Switzerland (in press).
- Federici, M. L., Gorrini, A., Manenti, L., Sartori, F. (2012). Festivalization of the City Support: A Case Study. *Metadata and Semantics Research*, 74-82.
- Federici, M. L., Gorrini, A., Manenti, L., Sartori, F. (2012). A Proposal of an Event Ontology for Urban Crowd Profiling. *International Workshop on Ontology, Models, Conceptualization and Epistemology in Social, Artificial and Natural Systems. 24th International Conference on Advanced Information Systems Engineering*, Gdansk, Poland, 97-104.

Figure 1.2: *The work flow of the thesis work, based on the application of the general framework of proxemics for the empirical investigation of pedestrian crowd dynamics: in vivo observations of pedestrian circulation dynamics, in vitro experiments of human locomotion-spatial behavior, in silicon simulation of pedestrian crowd what-if scenarios.*

2

The Social Science Contributions about Crowd Dynamics

The Chapter presents a comprehensive review of the social science framework about crowd dynamics. Starting from the pioneering study of Gustave Le Bon (1897), the first part of the Chapter presents the main theoretical approaches about the phenomenon: the Contagion-Transformation Theory, the Elaborated Social Identity Model and the Emergent Norm Theory. The second part (Section 2.5) is focused on crowd dynamics in situation of emergency (i.e. mass panic), with particular reference to the theoretical contribution of the Affiliative Approach. The Chapter ends with final remarks about the framework and its application towards the empirical investigation of pedestrian crowd dynamics.

2.1 Introduction

From the social science perspective (e.g., social psychology, crowd psychology, sociology, anthropology), the investigation of crowd dynamics is a complex research topic. The interest in studying the phenomenon started in the late 19th century, thanks to the pioneering work "*The crowd: A study of the popular mind*"of the french psychologist Gustave Le Bon (1897), who was mainly inspired by the growing urbanization and the need to control public order in case of mass demonstrations, violent riots and revolutions. Since then, the definition of crowds is still controversial, due to the lack of standard guidance for data collection and several ethical-practical restrictions (e.g. safety of individuals involved, costs of experiments or data acquisition). In this respect, crowds can be preliminary defined as gatherings of people with a common purpose or as a form of collective action:

> "*It is possible to define a crowd as two or more persons engaged in one or more common actions, or concerted on one or more dimensions (e.g. direction, speed, time or substantive content).*" (McPhail, 1991, p. 98)

According to the technical report "*Understanding Crowd Behavior*"(Challenger et al., 2009), commissioned by the Cabinet Office of the Government of the United Kingdom and published as a part of UK Civil Protection Guidance, one of the most accepted definition of what a crowd is cites as below:

> "*A crowd can be defined as a gathering of twenty people (at least), standing in close proximity at a specific location to observe a specific event, who feel united by a common social identity and who are able to act in a socially coherent way, despite being strangers in an ambiguous or unfamiliar situation.*" (Challenger et al., 2009, p. 43)

Starting from these preliminary definitions, we present a synthetic classification[1] of the main theoretical contributions about crowd dynamics: the Contagion and Transformation Theory (Sec. 2.2), the Elaborated Social Identity Model (Reicher, 2001) and the Emergent Norm Theory (Turner and Killian, 1987) (respectively presented in Sec. 2.3 and Sec. 2.4). Considering recent crowd disasters, the second part of the Chapter presents the main theoretical contribution about crowd dynamics in emergency situations (Sec. 2.5), with reference to the Mass Panic Approach, the Elaborated Social Identity Model, the Emergent Norm Theory and the Affiliative Approach. The Chapter ends with final remarks about the application of the presented framework towards the empirical investigation of pedestrian crowd dynamics.

2.1.1 Classification of Different Types of Crowd

The difficulty to reach an exhaustive definition of crowd is linked to the variability among size and typology of the phenomenon. Crowd behavior depends on the combination among the physical features of the environment and situational factors (e.g., social context, collective goal, individual motivation to participate, introduction of alcohol or drugs). For this reason, the comprehensive definition of crowd dynamics needs to take into account both physical and contextual aspects, and their mutual interaction (i.e. *crowd profiling*) (Health and Executive, 1999).

In this respect, Gustave Le Bon (1897) proposed a classification of different types of crowd, distinguishing between: heterogeneous crowds (e.g., anonymous street crowds, planned assemblies crowds) and homogeneous crowds (e.g., political, religious, military, sacerdotal, bourgeois and working men crowds). Herbert Blumer (1951) attempted a further classification, differentiating among: casual crowd (a contingent collection of people that simply encounters in the same place at the same time, like people in a shopping center, without displaying a real social interaction), conventional crowd (a prearranged meeting of people, like political meetings), expressive crowd (a crowd that is animated by a strong emotional motivation, like political demonstration marches), acting crowd (a crowd that has the purpose to perform a specific action) and

[1] The proposed theoretical framework is classified into distinctive categories that have not to be considered as absolute, since some of them present traits that can also be attributed to others, as well as some of the used indicators could identify more than one theory and approach.

protest crowd (a crowd that is characterized by possible violent behavioral dynamics, directed to a specific target).

Elias Canetti (1962) proposed an alternative classification of the phenomenon, based on several characteristics of crowds: the attitude to grow and become denser, the physical proximity among members, the differences in the nature of goals, the transformation of single members in a collective entity where individual differences are dropped. On the basis of these criteria, Elias Canetti codified three dichotomous categories of crowd: open-closed, stagnating-rhythmic and quick-slow crowds. More recently, in the context of crowd management[2] during large urban events, Berlonghi (1995) identified eleven different types of crowds, among which: spectator crowd (watching the activities of an event or at the scene of an accident), demonstrator crowd (organized by some established leadership), violent crowd (attacking, terrorizing and rioting with complete disregard for laws and the rights of others), escaping crowd (attempting to escape from danger either of an actual or imagined threat).

2.2 Contagion and Transformation Theory

In his pioneering work Gustave Le Bon (1897) defined crowds as potential threats to society. This statement is based on the definition of crowd members as people who display an altered states of consciousness, with a consequent lose of sense of self-awareness and irrational-violent behavior. According to this approach, some others theoretical contributions (Tarde, 1893; Sighele, 1901) defined people within the crowd as "creatures of passion", overwhelmed by irrationality and unable to exercise the most elementary forms of cognition:

> "*A crowd is not just a gathering of people, since it is based on the predominance of the unconscious personality of members, suggestion and contagion of feelings and the idea of an identical direction of action [..]; these are the principal characteristics of the individuals forming part of a psychological crowd.*"(Le Bon, 1897, p. 35)

This theoretical approach states that when people are gathered into a crowd they act as a single entity (Canetti, 1962) or as guided by a collective mind (Tarde, 1893), abandoning rationality and responsibility due to a feeling of power (Park et al., 1972). According to this perspective, the Social Deindividuation Theory (Festinger et al., 1952; Zimbardo, 1969) argued that being part of a group, especially large and anonymous such as a crowd, leads to a loss of personal identity, a minimization of self-observation and a diffusion of personal responsibility to social norms, with a consequent increase in antisocial behaviors.

[2]Although the terms are often used interchangeably, the *proactive* management of crowds includes the systematic planning of all the measures taken for facilitating the orderly movement and assembly of people, while the *reactive* control of crowds includes all the measures taken once members are beginning to or have got out of control, including extreme measures to enforce order (Fruin, 1993; Berlonghi, 1995).

In conclusion, the presented approach comprehends those contributions that consider crowd dynamics as based on irrational and violent behaviors. Mainly influenced by the need to control public order, this framework is still taken into consideration for the interpretation of many crowd phenomena, even if there are not empirical evidences about crowd members' antisocial behavior, not even in emergency situations. For these reasons the Contagion and Transformation Theory appears as a not exhaustive definition of the phenomenon.

2.3 Elaborated Social Identity Model

Far from the Le Bon's approach, the Elaborated Social Identity Model (Reicher et al., 1995; Reicher, 2001) rejects the dissolution of personal identity in the crowd, claiming that collective action is normal rather than irrational. The condition of anonymity typical of a crowd does not lead to a loss of control of individual behavior, but rather to an increase of group normative behavior. This is due to the spontaneous transition from an individual identity to a common social identity, as a model of self in social relations (Turner, 1981).

In particular, when people are anonymous members of a crowd they are more likely to express recognizable aspects of their common group identity, thanks to a process of self-categorization (Drury et al., 2009). This leads individuals to behave accordingly to what they believe is appropriate. Moreover, the social context has a predominant impact on collective actions, telling the difference between an aggregate of people and a psychological crowd (e.g., football supporters), as characterized by a common aim, a shared social identity and an emergent sense of "we-ness" (Drury and Cocking, 2007).

In conclusion, although the Elaborated Social Identity Model is mainly focused on crowd conflicts (e.g., political demonstration, crowd disorder), it was recently applied to support the definition of prosocial crowd dynamics, also during emergency situations (Drury et al., 2006).

2.4 Emergent Norm Theory

The Emergent Norm Theory (Turner and Killian, 1987) contributes in the understanding of crowd dynamics, focusing on the prosocial interactions among members. This is based on the interpretation of crowd behavior as not fully irrational, violent or antisocial, although it is predictable only with approximation. This approach is focused on the emergence of new normative structures among people within the crowd, by means of social interactions. In particular, crowd members adapt their behavior to new norms, that emerge from contingent contexts of collective action, by imitating assertive individuals (i.e. leadership).

According to this theory, a crowd can be initially defined as an unstructured and heterogeneous assembly of people. Then, to become a proper psychological crowd social interactions among members have to be focused on a new normative structure, that is different from the traditional ones and changes depending on the social context. This guides crowd members to act and interact in either pre-existing groups or impromptu groups, assuming social roles that are different from their actual status (Aguirre et al., 1998).

In conclusion, the Emergent Norm Theory received several critics due to the few attention that it pays to nonverbal processes that take place in a crowd. Moreover, it is argued that the assumed process of milling would need too much time to face critical contextual situations of collective action.

2.5 Crowd Dynamics in Emergency Situations

Recent crowd disasters[3] have highlighted the importance to properly manage mass gathering and transit places, and to adopt formalized procedures of evacuation to enhance the safety of people in case of emergency (Tarlow, 2002). The term mass panic is often-used to define crowd dynamics during emergency situations (Chertkoff and Kushigian, 1999): people attend to their own needs and do not care about the fate of others, due to an excessive feeling of alarm or fear. This can be defined as a set of non-adaptive collective behaviors, strictly linked with uncoordinated and simultaneous rushing toward the exit (stampede, pushing, crushing, and trampling), due to the scarceness of possibility to evacuate (Mintz, 1951):

> "*If some people are pushing, then an individual may feel that his/her chances of exiting safely are threatened if he/she does not react; the best course of action for the individual may be to join the competition and push, in order to maximize the chance of exiting safely.*"(Pan et al., 2006, p. 7).

Contrary to its representation in movies and mainstream media, the term mass panic[4] is not the most appropriate definition of crowd dynamics in emergency situations: people rarely lose control during evacuation, still following conventional social rules directed toward collaboration, also between strangers (McPhail, 1991; Clarke, 2002). Moreover, the definition of the term panic is not linked to collective behavior under emergency situations, since it refers to endogenous psychological and physiological factors related to individual panic attacks, defined as discrete and sudden periods of

[3] Such as: the Kiss nightclub fire on 27th January 2013 in Rio Grande do Sul-Brazil, that caused the death of 232 people and the wounding of 200 people; the stampede during the Love Parade on 24th July 2010 in Duisburg-Germany, where 21 people died and 510 others were injured; the Beverly Hills Supper Club fire on 28th May 1977 in Kentucky-U.S., that caused the death of 165 people and the wounding of 70 people.

[4] Although mass panic is not the most appropriate term to define crowd dynamics in emergency situations, since it exclusively refers to self-preservative response to danger, it is used in the thesis for an easier comprehension of the phenomenon.

intense anxiety and fearfulness, linked to both internal and external triggers[5] (DSM-IV, 1994).

Starting from this preliminary considerations, the second part of the Chapter presents the social theories about crowd dynamic in emergency situations, with reference to the Mass Panic Approach (Le Bon, 1897), the Elaborated Social Identity Model (Reicher, 2001), the Emergent Norm Theory (Turner and Killian, 1987) and the primary contribution coming from the Affiliative Approach (Mawson, 1978) (Section 2.5.4).

2.5.1 Mass Panic Approach

According to the Contagion and Transformation Theory, the Mass Panic Approach (Le Bon, 1897) states that the typical crowd members' response to danger is based on an excessive anxiety and fear (Smelser, 1962). Mass panic spreads in the crowd such as a contagion[6], through mutual imitation and suggestibility (Freud, 1965).

> "*Mass panic is based on hysterical believes [..]: an animal-like stampede, in which wildly excited people crush each other to death, referring to an internal feeling of intense terror or fear. [..] Having accepted a belief about some generalized threat, people flee from established patterns of social interaction in order to preserve life from that threat.*" (Smelser, 1962, p. 131)

Quarantelli (1954) suggests that mass panic arises when entrapment is sensed as a possibility and when people feel powerless and isolated. Self-preservative aggression and flight occur when escaping routes are limited or closing. According to this approach, mass panic is defined as a fear reaction marked by loss of self-control and followed by anti-social collective behavior. Collective bonds and norms break down and people behave irrationally and instinctively, competing with others during uncoordinated escape to danger.

> "*In a emergency situation, ordinary social relationships are disregarded and preexistent group action patterns fail to be applied.*" (Quarantelli, 1954, p. 270)

> "*A crowd in a state of panic act not corporately but individually. [..] If the psychological crowd is a society in being, mass panic is a society in dissolution.*" (Park and Burgess, 1921, p. 34)

[5]The Diagnostic and Statistical Manual of Mental Disorders (1994) defined a panic attack as associated with feelings of impending doom, and several symptoms: palpitations, sweating, trembling, shortness of breath, feeling of choking, chest pain, nausea, feeling dizzy, derealisation, fear of losing control, fear of dying, paraesthesia and chills or hot flushes.

[6]The emotional contagion is defined as the tendency to automatically mimic and synchronize facial expressions, vocalizations, postures and movements with those of another person and, consequently, to converge emotionally (Hateld et al., 2009, p.5).

2.5.2 Elaborated Social Identity Model

The Elaborated Social Identity Model (Reicher, 2001) states that crowd behavior is not irrational, even in case of emergency. Recently, it has been applied to investigate crowd disasters (Drury et al., 2006; Drury and Cocking, 2007), focusing on the interrelate impact of self categorization processes among crowd members and the features of the social context in which the emergency occurs. This approach contrasts to the typical representation of mass panic in mainstream media, defining crowd dynamics in case of emergency as characterized by coordinated and cooperative behaviors also among strangers, rather then irrational behavior (Cocking et al., 2009): panic is relatively rare and it only presents in few unrepresentative individuals.

> "*Having experienced a common fate, previously disparate crowd members come to see themselves as part of a common category [..]: this extension of the in-group category, along with the solidarity that is both expected and obtained among group members, lead to a sense of empowerment and a willingness to challenge the situation.*" (Reicher, 2001, p. 201).

2.5.3 Emergent Norm Theory

The Emergent Norm Theory (Turner and Killian, 1987) claimed that crowd behavior under emergency situations is not irrational, but social-normative also among strangers. In case of disaster, the emergence of a new normative structure is driven by the contextual situation, that is collectively perceived and interpreted in order to act appropriately (Aguirre, 2005). In particular, the crisis creates a sense of uncertainty and urgency that forces people to abandon their established normative guidelines and to interact in either pre-existing or impromptu groups (Aguirre et al., 1998).

> "*Forced by the crisis to abandon their previously established social relationships, statuses and normative guidelines regarding legitimate ways of acting, people engage in collective behavior to solve the crisis, reconstituting groups and social relationships.*" (Aguirre, 2005, p. 5).

According to this approach, the ability to act in a normative and social manner in case of crowd disaster is linked to the physical features of the scenario in which the hazard occurs, and its nature (Aguirre, 2005). Moreover, thanks to the presence of heterogeneous actors with different abilities to respond to the crisis, the collective action is guided by an emergent group leadership (Turner and Killian, 1987).

2.5.4 Affiliative Approach

The Affiliative Approach (Mawson, 1978, 2005) proposes a prosocial conception of crowd dynamics, stating that everyday social roles and norms continue to shape members's behavior while facing the emergency (Johnson, 1987). This approach states that, even if crowd crushes in disaster situations and appears to involve elements of competitive and selfish behavior, collective behavior is based on social bonds (Mawson, 2007). Despite variations in the nature of disaster, people continue to be social beings who care for others, trying to remain in groups during evacuation.

> "*The traditional conceptions of crowds failed to consider the impact of human relationships and, in particular, how such relationships would both affect and be affected by social crisis. Even in cases where people were clearly fleeing from a given threat or hazard, there were significant increases in affiliative behavior immediately and for considerable time after the event.*" (Mawson, 2007, p. 2).

This approach is based on the Attachment Theory (Bowlby, 1969): during emergency situation both animal and human data showed that being at the presence of familiars has a calming effect, whereas the opposite is true if one is alone, with strangers or in unfamiliar surroundings.

The Affiliative Approach states that, in case of emergency, social ties evidently increased in strength: individuals refer to other primary group members to define the situation, and move towards familiar persons and familiar places as a characteristic of preflight and flight behavior (Mawson, 1978; Sime, 1983). Moreover, the Attachment Theory states that the affiliative behavior in stressful situations can be defined as an evolutionary adaptive mechanism (Mawson, 2007). *Proximity-seeking* among group members is a tropism-like response (i.e. automatic turning movement in response to an environmental stimulus), that involves sensory stimulation via physical contact and social interaction.

Therefore, the Affiliative Approach (Sime, 1983, 1995) is focused on how the presence of groups within the crowd affects the time for crowd evacuation (T) (as illustrated in Fig. 2.1). The main assumption is that T is composed of the time for people to start to move (t_1) and to reach and pass through exits (t_2), rather than T=t_2. In particular, t_1 is influenced by group preflight behavior, based on proximity seeking among members to define the situation, act in a social way and remain together throughout the egress process.

In conclusion, the Affiliative Approach states that the typical crowd members' response to danger is based on affiliative behavior. Family and/or friendship ties remain strong within the crowd, even during highly stressful situations, with mutual cooperation predominating within these groups (including people returning to the place they evacuated in order to help others, try to rescue friends and salvage important belongings), as opposed to selfish and uncooperative behavior (Johnson, 1987). Flight and selfish behavior are more likely when in a crowd of strangers or since traditional social roles appear to have broken down (Cornwell, 2003).

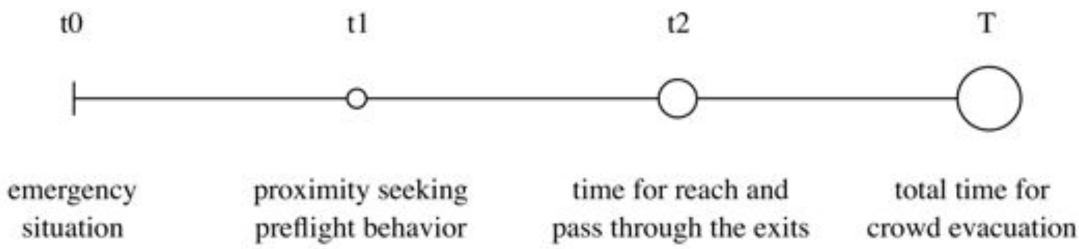

Figure 2.1: *According to the Affiliative Approach (Sime, 1995), the total time for crowd evacuation in case of emergency (T) is composed of group preflight behavior (t_1), defined as proximity seeking among members to define the situation and act in a social way, and the time for people to reach and pass through exits (t_2).*

2.6 Final Remarks

The Chapter presented a comprehensive overview of the main theoretical contributions about crowd dynamics, considering both ordinary and emergency situations. Starting from the pioneering study of the french psychologist Gustave Le Bon (1897), the definition of crowds is still controversial, due to the lack of standard guidance for data collection and the variability among size and typology of the phenomenon.

The first part of the Chapter presents some preliminary definitions and classifications of the phenomenon (see Section 2.1.1). Then, the Chapter proposes the systematic review of main social science contributions, considering both normal and emergency situations (the Contagion and Transformation Theory, the Mass Panic Approach, the Elaborated Social Identity Model, the Emergent Norm Theory and the Affiliative Approach), as summarized below:

- Contagion and Transformation Theory - Mass Panic Approach (Le Bon, 1897):
  - *Crowd Dynamics*: as anonymous members of a crowd, people lose their sense of self-awareness and personal identity, with consequent antisocial and irrational behaviors;
  - *Crowd Dynamics in Emergency Situations*: uncoordinated self-preservative aggression or flight are the typical responses to danger. Collective bonds and norms break down, as people behave irrationally, competing with others;
  - *Limitations*: the approach highlights limited assumptions about crowd dynamics, as it exclusively defines members's behavior as irrational and violent. The theory is not supported by empirical evidences.
- Elaborated Social Identity Model (Reicher, 2001):
  - *Crowd Dynamics*: the anonymity typical of a crowd does not lead to a loss of control on individual behavior, but rather to group normative behavior;

  - *Crowd Dynamics in Emergency Situations*: crowd members develop a sense of membership that encouraged cooperative behaviors in case of emergency (panic only presents in few unrepresentative individuals);
  - *Limitations*: the approach is mainly focused on crowd conflicts, such as political demonstrations and disorder.

- Emergent Norm Theory (Turner and Killian, 1987):
  - *Crowd Dynamics*: collective behavior is not irrational, but social-normative and oriented toward a shared goal;
  - *Crowd Dynamics in Emergency Situations*: the sense of urgency create a new emergent normative structure that guides collective behavior;
  - *Limitations*: the approach is mainly focused on emergency situations in which it is possible to develop complex lines of social action.

- Affiliative Approach (Mawson, 1978):
  - *Crowd Dynamics in Emergency Situations*: family and/or friendship ties remain strong in the crowd, with mutual cooperation among members. The typical response to danger is to seek the proximity of familiar persons, trying to evacuate within them, as opposed to selfish and uncooperative behavior;
  - *Limitations*: the approach neglects the possibility of cooperative behavior between those who had no existing attachment bonds, or that attachment bonds could develop quickly between strangers.

Although the terms crowd dynamics and pedestrian crowd dynamics are often used interchangeably, it has to be underlined a substantial distinction among them in order to make clear the approach that sets the thesis work. First, the term *crowd dynamics* generally refers to complex levels of social interaction among crowd members in static situations. This conceptualization is well summarized by Challenger et al. (2009), who define a crowd as a gathering of people, who feel united by a common social identity and who are able to act in a socially coherent way despite being strangers.

On the other hand, the term *pedestrian crowd dynamics* refers to more simple levels of social interaction among crowd members in motion situations. In particular, this is focused on pedestrian flow dynamics in situation of high density (e.g., competitive spatial interactions among commuters while walking in a crowded transport facility). This approach is clearly stated in the definition of *casual crowd* proposed by Blumer (1951): a contingent collection of people, who encounters in the same place at the same time, without displaying complex social interactions.

According to that, the thesis work is aimed at analytically investigating pedestrian crowd dynamics, focusing on pedestrian circulation dynamics in situations of variable density and human locomotion-spatial behavior (considering both individual and group levels of investigation).

3

Proxemic Behavior, Grouping and Pedestrian Dynamics

The Chapter presents a comprehensive review of the proxemic theory (Hall, 1966). This is aimed at supporting the empirical investigation of human spatial behavior during locomotion in situation of variable density, considering both individual and group level of investigation. In particular, the Chapter includes the systematic definition of proxemics (Section 3.2) and the notion of personal space (i.e. the area immediately surrounding individuals, into which strangers cannot intrude without arousing discomfort, Section 3.3). The proxemic behavior of group members in static and motion situations is presented in Section 3.4. The Chapter ends with final remarks about the framework and its application towards the empirical investigation of pedestrian crowd dynamics.

3.1 Introduction

The Chapter includes a comprehensive overview of the most relevant social science contributions about *proxemics* (Hall, 1966) (e.g., environmental psychology[1], sociology, anthropology). This is aimed at focusing on pedestrian crowd dynamics from the analytic perspective of the proxemic theory, thanks to its ability to model the social interactions among people and groups as they interact.

Since the study of human spatial behavior is mainly focused on static situations of social interaction, this work is aimed at extending the general framework of this theory towards the investigation of proxemic behavior during locomotion, considering both individual and group levels of investigation. This is aimed at improving the understanding of the impact of grouping (i.e. social units characterized by common goals and variable strength of membership) on pedestrian crowd dynamics. Starting from these preliminary considerations, the Chapter is particularly focused on:

[1] Environmental Psychology emerged as autonomous discipline from Behavioral Science and Social Psychology during the 1960s, focusing on the impact of the social and physical features of the environment on human behavioral outcomes related to perception, cognition, learning and development (Stokols and Altman, 1987).

- *proxemics*: in analogy with territorial behavior in animals, Edward T. Hall (1966) introduced the term proxemics for the study of human spatial behavior, as a type of nonverbal communication that conveys information about the nature of participants' relationship outside the spoken language. The work is aimed at applying the general framework of proxemics to characterize the social and spatial interactions among crowd members during locomotion;
- *groups*: defined as two or more people who interact to achieve a common goal, perceiving a sense membership (Turner, 1982), groups are the basic interacting elements that compose a crowd (e.g., relatives, friends). Both in normal and emergency situations, pedestrian crowd dynamics are influenced by the presence of groups, which generate patterns of movement generally respected by other pedestrians (Mawson, 2007);
- *density*: the physical features of the environment significantly impact pedestrian crowd dynamics. Due to the lower degree of freedom for spatial positioning, critical situations of high density are characterized by competitive interactions among pedestrians (Fruin, 1971) and crowding (Baum and Paulus, 1987), a physiological and psychological response of stress.

The Chapter presents the proxemic theory (Hall, 1966), with reference to the dynamics regulation of interpersonal distances during social interaction (Section 3.2) and the notions of personal space (Section 3.3) and crowding (Sec. 3.3.2). The proxemic behavior of groups is illustrated in Section 3.4, with reference to both static and motion situations. The Chapter ends with final remarks about framework and its employment towards the investigation of pedestrian crowd dynamics.

3.2 Proxemic Behavior

In analogy with territorial behavior in animals[2] (Hediger, 1961), the anthropologist Edward T. Hall (1963, 1966) introduced the term proxemics for the study of human spatial behavior. In particular, proxemics is a type of nonverbal communication that conveys important informations about the nature of participants' relationship outside the spoken language (as well as facial expressions, kinesics and visual behavior), both to themselves and to the observers. Proxemic behavior is based on the definition of four interaction zones (Hall, 1966), which reflect the principal categories of social relationships among human beings (Bell et al., 1978):

[2] Territoriality is the way by which animals in the wild characteristically claim to an area and defends it against conspecifics (Hediger, 1961). In particular, animal territorial behavior is based on the spatial definition of four interaction zones: flight distance (run boundary), critical distance (attack boundary), personal distance (separating members of non-contact species) and social distance (intra-species communication distance).

1. *intimate distance* (0 m-0.45 m): intimate interaction with physical contact (intense awareness of sensory inputs, such as smell and radiant heat; touch overtakes vocalization as primary mode of communication);

2. *personal distance* (0.45 m-1.20 m): physical contact between close friends, as well as everyday interaction among acquaintances (limited awareness of sensory inputs; verbal channel accounts a more direct communication rather than touch);

3. *social distance* (1.20 m-3.60 m): business-like social interaction (minimal sensory inputs, limited information provided by visual channel; a normal voice level is maintained, physical contact is not possible);

4. *public distance* (3 m-6 m): formal interaction between an individual and the public (no sensory inputs; exaggerated nonverbal behaviors employed to supplement verbal communication).

The regulation of spatial interpersonal distances is based on a dynamic equilibrium (Argyle and Dean, 1965): people look for an optimal level of closeness with others during social interactions. If acquaintances come too close or stay too far away disturbing this equilibrium, compensatory verbal and nonverbal behaviors will be used, as a dynamic readjustment of spatial distances (Hayduk, 1978).

Proxemic behavior is influenced by several variables, such as attraction, age, gender, culture, similarity and personality. Closer distance is an outcome of increased attraction and friendship (Aiello, 1987). Young people approach one another more closely than older individuals (Hayduk, 1978). Females show intimate distances more frequently than males (Aiello, 1987). In *high-contact cultures* (e.g., Mediterranean, Arabic, Hispanic cultures), people exhibit closer distances than *no-contact cultures* (e.g., Northern European, Caucasian American cultures) (Hall, 1966; Aiello, 1987). Similarity in ethnicity, religion, sexual preference and status elicit closer interpersonal positioning (Bell et al., 1978). Anxious individuals and individuals with low self-esteem maintain larger distances (Patterson, 1976).

3.3 Personal Space

The need of optimal reciprocal distances with other people is driven by psychological factors and social norms related to the notion of *personal space* (Sommer, 1969): the area immediately surrounding individuals, into which strangers cannot intrude without arousing discomfort. In analogy with the intimate distance, personal space represents a boundary regulation mechanism around the human body, intended to to achieve desired levels of privacy (Altman, 1975) and to protect themselves from physical and psychological threats (Evans and Howard, 1973).

3.3.1 Shape of Personal Space

The shape of personal space is commonly represented as a circular area surrounding individuals (Hall, 1966). However, this definition does not adequately characterize the flexibility of this body buffer zone in relation to human distance receptors (including visual, auditory, olfactory and thermal receptors). In particular, the asymmetrical shape of personal space is related to the subject's head orientation and visual mechanism: the front and lateral zones are slightly larger than the rear zone (Hayduk, 1983) (as illustrated in Fig. 3.1).

Although innovative results have been recently achieved regarding the neural substrates of personal space as mediated by amygdala activation functions (Kennedy et al., 2009), only few empirical contributions investigated the spatial configuration of personal space during locomotion. For instance, according to the seminal work of John J. Fruin (1971) the front zone of pedestrian personal space is defined as composed of a pacing zone for foot placement and an elliptical sensory zone, that is necessary to perceive, evaluate and react in time to environmental stimuli, i.e. locomotor vision (Gibson, 1950).

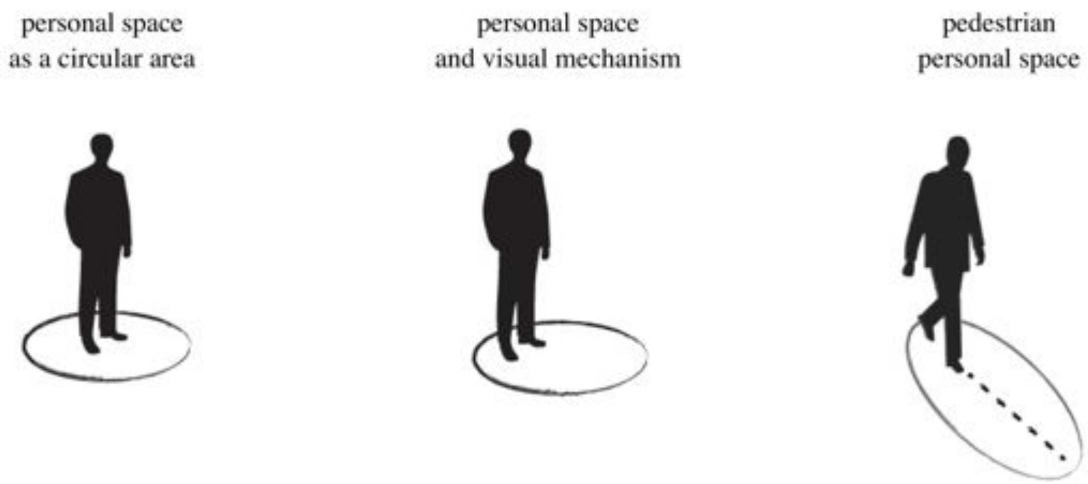

Figure 3.1: *As illustrated from the left to the right side: the spatial configuration of personal space in (i) static situations (as a circular area surrounding human body or as a flexible area related to head orientation) and (ii) motion situations (as characterized by an additional margin in the front zone to perceive and react in time to environmental stimuli).*

3.3.2 Invasion of Personal Space, Density and Crowding

The condition of inappropriate proximity with others or spatial restriction in situation of high density represents a stressful factor strictly linked with *crowding* (Baum and Paulus, 1987). Density (the quantitative relationship between a given physical area and the number of people who occupy it[3]) is necessary but not sufficient by itself to elicit the subjective experience of crowding (Stokols, 1972). This is related to: (*i*) the violation of normative expectations about the invasion of personal space and the consequent cues of threat (Baum and Paulus, 1987), (*ii*) the behavioral restriction and frustration of goals related to the physical presence of others, (*iii*) the inability to use verbal and nonverbal coping responses to control inappropriate social contacts (e.g., head movements away from others, reduced level of eye contact as an initiator of social interaction) (Goffman, 1963; Evans, 1979), (*iv*) an excessive sensory stimulation that negatively influences individual's perception of the space[4] (Appleton, 1984).

In analogy with animal behavior[5] (Calhoun, 1962), crowding is a pathological stressor mediated by endocrine responses (i.e. corticosteroids hormones released by the adrenal cortex) (Baum and Paulus, 1987). The psychological and physiological responses to crowding are typically associated with arousal and stress (e.g., skin conductance, cardiovascular response, rising blood pressure, palmar sweating and endocrine activity) (Aiello et al., 1975), cognitive performance decrements in complex tasks (Evans, 1979) and some aftereffects, including reducing tolerance for frustration and aggressive response (Aiello et al., 1979).

The occurrence, magnitude and persistence of crowding depend on several factors related to individual's preference in spatial positioning. People who prefer larger interpersonal distances during social interaction appear to be more negatively affected by density (Aiello et al., 1977). Male exhibit more aggressive responses and withdrawal tendencies under crowded conditions than female (Freedman et al., 1972). Crowding in primary environment (e.g., home, classroom) has more significant effects than relatively unimportant environments (e.g., shopping center) (Stokols, 1972; Altman, 1975). The physical and architectural features of the environment mediate the subjective experience of crowding, considering comparable situations of physical density (Baum and Paulus, 1987). 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 (e.g., concerts, sport events) (Patterson, 1976).

[3] A more detailed definition of density considers also the difference between social density (obtained varying the amount of people and holding constant the available space in a given area) and spatial density (obtained varying the amount of available space while holding constant the number of people) (Stokols, 1972). The argument is that these two types of density are experienced differently in terms of crowding (Baum and Paulus, 1987).

[4] The Prospect-Refuge Model (Appleton, 1984) postulated that human beings prefer settings with prospect (open view) and refuge (concealment, protection), because such places aided survival from hazards by offering an observation point to see, to react and if necessary to defend.

[5] Calhoun (1962) defined the distribution of large number of animals in situation of high density as related to the development of non-adaptive behavioral pattern (i.e. *behavioral sink*) based on crowding. Thus while the impact of crowding on human beings is influenced by an unique adaptive abilities, some of the variables causing or mediating crowding are similar for both humans and animals.

3.4 Group Proxemic Behavior

Group proxemic behavior operates analogously respect to individuals (Knowles, 1973). The boundaries of the social space shared by group members during social interaction serve to: facilitate communication, express to others rather general knowledge about the strength of the social ties that hold the group together, maintain a personal comfortable range of proximity, shield group members from unwanted interactions with other people or groups (Sommer, 1969; Patterson, 1976; Sundstrom and Altman, 1976), mitigate the effects of crowding by maintaining spatial cohesion and increasing intergroup distances (Baum et al., 1975).

In static situations of social interaction the functional space shared by group members can be defined as composed of three different zones (i.e. *F-formation*) (Kendon, 1990): (*i*) the inner shared space, that participants actively cooperate to sustain during conversation, (*ii*) the space for participants placement and (*iii*) the space that surrounds participants and serves as a kind of buffering zone. Depending on the number of group members, the shape of social space assumes different configurations in order to facilitate social interact: face to face and side by side spatial layout for dyads, L-like configuration and circular disposition for groups composed of three or more members.

3.4.1 Proxemic Spatial Arrangement of Walking Groups

In analogy with static situations, the spatial behavior of walking groups reveal important nonverbal information about the strength of the psychological bonding among the members (e.g., spatial cohesion and proxemic arrangement during locomotion) (Knowles and Brickner, 1981; Wesley Burgess, 1989). In particular, depending on the level of density in the environment and the presence of physical constraints induced by obstacles, the proxemic behavior of walking group generates typical patterns of spatial arrangement (Costa, 2010; Moussaïd et al., 2010) (as illustrated in Fig. 3.2).

At low density, group members walk side by side, forming a line perpendicular to the walking direction (i.e. *line abreast pattern*). As the density increases, the linear walking formation turns into a *V-like pattern*, with the middle individual positioned slightly behind in comparison to the lateral ones. This pattern facilitates social interactions, since each member can easily see the others with a slight head movement, but it reduces the group walking speed due to its misaligned shape.

In situation of high density, in order to minimize collisions with other pedestrians, the spatial distribution of the group members leads to a *river-like pattern*, characterized by the presence of a leader that coordinates group members while crossing the space[6]. This pattern is characterized by limited opportunities for verbal communication, how-

[6]The emergence of a group leadership among pedestrians occurs in case of a greater availability of space or a deliberate appropriation of space. Moreover, it is closely related to the situational features of the context, the strength of the social ties that hold the group together and the status of each member (Daamen and Hoogendoorn, 2003).

ever group members are still able to communicate by means of short verbal messages (by turning his head-torso or even his whole body toward the other members that follow) (Costa, 2010).

Figure 3.2: *As illustrated from the left to the right side: the typical proxemic spatial patterns of walking groups (line abreast, V-like and river- like patterns), related to the physical constraints induced by the presence of obstacles and the level of density in the environment.*

The number of members and their status, gender and age influence group proxemic behavior (Knowles, 1972). Line abreast, V-like and river-like proxemic patterns are related to small groups distribution. Groups composed of more than three members split themselves into single individuals, dyads and triads (Costa, 2010) or to turn to other spatial configurations like spherical and ellipsoidal (Moussaïd et al., 2010). Lastly, male dyads and triads walk less often abreast than female; adolescents and young adults walk in groups more than adults and old people (Costa, 2010).

3.5 Final Remarks

The Chapter proposed a systematic review of the *proxemic theory* (Hall, 1966). This was aimed at supporting the analytical investigation of pedestrian crowd dynamics, focusing on social and spatial interactions among pedestrians in situation of variable density (considering both individual and group level of investigation).

According to Edward T. Hall (1963, 1966), proxemics is defined as a type of non-verbal communication, based on the dynamic regulation of interpersonal distances among people and groups as they interact. Moreover, it is linked with the notion of personal space (Sommer, 1969): the area immediately surrounding individuals, into which strangers cannot intrude without arousing discomfort (as illustrated in Fig. 3.1).

The spatial restriction in situation of high density is a stressful condition strictly linked with *crowding* (Baum and Paulus, 1987): a psychological and physiological response of arousal and stress, typically associated with cognitive performance decrements, reducing tolerance for frustration and aggressive behavior.

In analogy with personal space, the space shared by group members serve to maintain a personal comfortable range of proximity and to shield group members from unwanted interactions with other people or groups (Knowles, 1973). Depending on the level of density, the proxemic behavior of walking group is characterized by typical spatial patterns (as illustrated in Fig. 3.2), in order to maintain cohesion and facilitate communication among members during locomotion (Costa, 2010).

Considering the reciprocal competitive interactions among people and groups within the crowd, due to the low degree of freedom for spatial positioning, the Chapter was aimed at characterizing the impact of proxemics and grouping on pedestrian crowd dynamics. In conclusion, we highlighted several indicators related to both individual and group proxemic behavior during locomotion (e.g., pedestrian personal space, spatial arrangements of walking groups), in order to contribute in the design of empirical studies related to pedestrian crowd dynamics (e.g., unobtrusive observation of pedestrian circulation dynamics in situation of variable density, experimental investigation of human locomotion-spatial behavior).

4 The Methodological Approach

The Chapter presents the methodological approach that sets the thesis work. In this respect, Section 4.2 presents the application of unobtrusive observations to investigate pedestrian circulation dynamics in urban crowded scenarios (e.g., crowd estimation, crowd composition, crowd profiling). The experimental method is presented in Section 4.3, with reference to its specific contribution for the investigation of human locomotion-spatial behavior. The contribution of pedestrian crowd simulations is presented in Section 7, with reference to the simulation platform MAKKSim (developed by the CSAI research center of the University of Milano-Bicocca). The Chapter ends with final remarks about the proposed methodological approach and its application towards the empirical investigation of pedestrian crowd dynamics.

4.1 Introduction

The methodological approach that sets the thesis work is composed of two empirical methods for data collection: (*i*) the unobtrusive observation of pedestrian circulation dynamics in urban crowded scenarios and (*ii*) the experimental investigation of human locomotion-spatial behavior in controlled laboratory setting. This is aimed at defining descriptive sets of metrics and parameters for characterizing the phenomenon and improving pedestrian crowd simulation platforms.

In order to finalize simulations into decisions and operational steps it is necessary to validate computational models, facing empirical evidences about pedestrian crowd dynamics. At this stage, the contribution of social science plays a crucial role for the understanding of human locomotion behavior (considering both individual and group levels of investigation).

The proposed interdisciplinary approach is based on the mutual integration between the analysis (e.g., empirical investigations) and synthesis (e.g., modeling and simulations) of pedestrian crowd dynamics. In particular, the proposed methodology can be synthetically represented as a virtuous cycle composed of: *in vivo* observation, *in vitro* experiment and *in silico* simulation (see Figure 4.1).

In this respect, Section 4.2 presents the observational method and its application to the investigation of pedestrian circulation dynamics, considering both data collection (e.g., scenario analysis, observational setting, duration time, staff, equipment, authorization) and data analysis (e.g., crowd estimation, crowd composition, crowd profiling, human locomotion and spatial behavior). The experimental method is presented in Section 4.3, with reference to its specific contribution for the investigation of human locomotion-spatial behavior, with reference to data collection (e.g., hypothesis, sample, setting, procedure, authorization) and data analysis (e.g., human locomotion and spatial behavioral indicators).

The contribution coming from computer-based simulations of pedestrian crowd what-if scenarios is presented in Section 7, with reference to different approaches in modeling the phenomenon (e.g., pedestrians as particles, cells or agents) and the simulation platform MAKKSim (developed by the CSAI research center of the University of Milano-Bicocca). The Chapter ends with final remarks about the proposed methodological approach and its application towards the empirical investigation of pedestrian crowd dynamics.

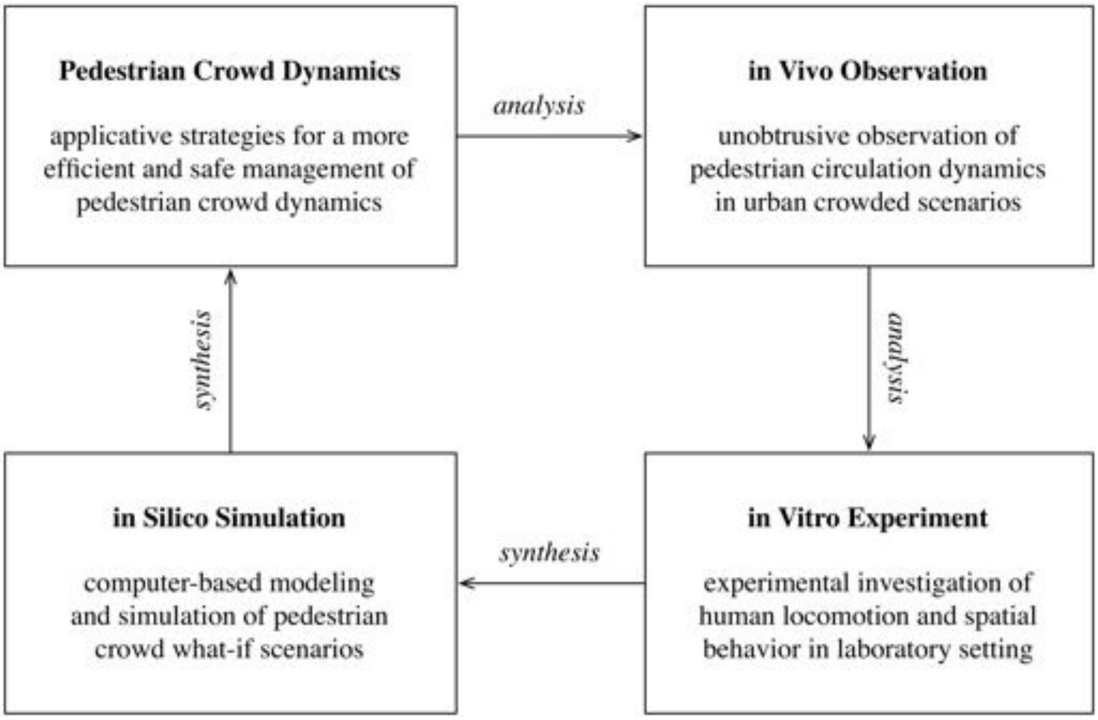

Figure 4.1: *The adopted methodological approach for the empirical investigation of pedestrian crowd dynamics, based on the integration among: in vivo observations of pedestrian circulation dynamics, in vitro experiments of locomotion-spatial behavior and in silico simulations of pedestrian crowd what-if scenarios.*

4.2 In Vivo Observation

From the social science perspective, the use of on field observations permits to collect empirical data about human behavior, considering the environment and the social context in which the subjects are situated (Schinka et al., 2003). Essentially, the difference between performing observations in natural settings and controlled experiments in laboratory settings is based on the possibility to exert a limited amount of control over the environment in which the empirical study takes place. One of the most crucial aspect in performing observations is that the merely presence of the observer has an impact on subjects' behavior, in terms of performance and social interaction (i.e. *Hawthorne effect*) (Adair, 1984). Starting from these preliminary considerations it is possible to classify two different types of observations (Goodwin, 2009):

- *observation without intervention*: also known as naturalistic observation, this methodology permits to study how human beings behave in a given natural setting, without any kind of intervention on the observed scenario. A further distinction can be operated between obtrusive observations (the subjects are aware to be observed) or unobtrusive observation (the subjects are not aware to be observed). Naturalistic observations permit to collect empirical data about rare phenomena that are difficult to be studied in laboratory setting, due to ethical and practical reasons. This method is limited by the impossibility to control variables and some ethical restrictions concerning the privacy of the observed subjects without their consent.

- *observations with intervention*: this methodology permits to control and manage a stimulus event that normally occurs infrequently in the observed scenario, in order to observe subjects' behavioral response. A further distinction can be operated among: participant observation (the observer has the same experiences of the observed subjects, strongly limiting the reliability of results), structured observation (the observer intervenes on the setting by means of the collaboration of a confederate) and on field experiments (the observer intervenes on the observed scenario to determine the effect on subjects' behavior).

According to Schinka et al. (2003), the informations acquired throughout the observational method can be collected and processed by using qualitative indicators (e.g., narrative notes) or quantitate ones (e.g., measurement scales, statistical tests). Moreover, data can be collected on site during the survey or by using technologies for video footages or audio record. Considering both these options, it is 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.

4.2.1 Unobtrusive Observation of Pedestrian Circulation Dynamics

This Section presents the application of the observational method for the investigation of pedestrian circulation dynamics in urban crowded scenario, focusing on both data collection (e.g., scenario analysis, observational setting, duration time, staff, equipment, authorization) and data analysis (e.g., crowd estimation, crowd composition, crowd profiling, human locomotion and spatial behavior).

Data Collection

Due to the complexity of the overall phenomenon, several practical factors has to be considered in order to design and perform on field observations of pedestrian circulation dynamics: the selection of the urban scenario in which the observation takes place, the systematic planning of the setting, the duration time of the survey, the involvement of staff members, the use of professional equipment for data collection and the authorization required to carry out the study.

- *Scenario Analysis*: in order to observe pedestrian circulation dynamics in urban scenarios it is possible to focus on mass gathering places (e.g, entrance and exit processes from a venue during a crowded event) or mass transit places (e.g., pedestrian flows in a public transport facility);
- *Observational Setting*: due to the large amount of people to observe and the space they occupy, the observational setting is a specific portion of the scenario. Preliminary inspections are needed to check its representativeness compared to the overall phenomenon. The equipment for video footages has to be positioned from a zenith point of view (to avoid images distortion and trajectories occlusion) and an hidden location (to not influence subjects' behavior). The physical features of the setting can enhance the success of the survey, considering both data collection and analysis (e.g., the presence of a roof top avoids that in case of a rainy day the presence of umbrellas would occlude pedestrians, the annotation of spatial reference points allows to estimate the inclined perspective of the images);
- *Duration Time*: it has to be planned considering its representativeness compared to the overall phenomenon (e.g., temporary entrance and exit processes from a crowded venue, continuos pedestrian flows in a public transport facility);
- *Staff*: the members of the staff (e.g., supervisor and confederates) have to be previously briefed about the objectives of the survey, considering also eventual limitations and critical aspects;
- *Equipment*: checklists or worksheets (on-site notes), full HD video cameras with wide lens and tripods (video footages), mobile phones or walkie-talkie (staff communication during the survey);

- *Authorization*: the video recorded observation of urban scenarios often needs the official authorization of the local Municipality. The existing legislation about privacy has to be consulted and complied in order to exceed some ethical issues about the privacy of the people recorded without their consent.

Data Analysis

The observation of pedestrian circulation dynamics is based on both *macroscopic* (e.g., crowd estimation, composition and profiling) and *microscopic* indicators (i.e., human locomotion-spatial behavior) of the overall phenomenon. Data analysis can be performed manually or by using automatic computer-based techniques (considering the level of maturity of video processing tools for people tracking).

- *Crowd Estimation*: this is based on people counting activities, aimed at estimating the level of density (defined as the quantitative relationship between the number of people and the physical area they occupy) and the *level of service* (LOS) (Fruin, 1971) in the observed scenario (by counting the number of people walking through a certain unit of space-meter, in a certain unit of time-minute) (see Fig. 4.2);

Level of Service	Flow Rate *(pedestrian/minute/meter)*	Density *(pedestrian per squared meter)*
A	≤ 7	≤ 0.08
B	7 - 23	0.08 - 0.27
C	23 - 33	0.27 - 0.45
D	33 - 49	0.45 - 0.69
E	49 - 82	0.69 - 1.66
F	≥ 82	≥ 1.66

Figure 4.2: *The level of service criteria (Fruin, 1971) defined a range of values to standardly describe the impact of contextual situations of density on pedestrian flows: LOS A corresponds to free flows, while LOS F corresponds to critical situations of high density with extremely difficulty in walking movements.*

- *Crowd Composition*: this is based on detecting the presence groups in the streaming of passersby considering verbal and nonverbal communication among crowd members (e.g., talking, gesticulation, visual contact, body orientation, proxemic spatial arrangement) (Costa, 2010);

- *Crowd Profiling*: this is focused on the socio-demographic characteristics of the observed subjects, checked from the recorded video images or by using questionnaires and data sets (e.g., ticket office information, subscription list);
- *Human Locomotion and Spatial Behavior*: this is focused on locomotion and proxemic behavioral indicators, considering both individual and group level of investigation: trajectories, walking speed, collision avoidance dynamics, group proxemic arrangement and spatial dispersion during locomotion, pedestrian competitive interactions in high density situations.

Unobtrusive Observation of Pedestrian Circulation Dynamics	
Data Collection	
Scenario Analysis	*mass gathering and transit place*
Observational Setting	*locations for video footages, physical features*
Duration Time	*representativeness*
Staff	*supervisor, confederates*
Equipment	*HD cameras, tripods, checklist, walkie-talkie*
Authorization	*Municipality permission, privacy legislation*
Data Analysis	
Crowd Estimation	*people counting, density, level of service*
Crowd Composition	*grouping*
Crowd Profiling	*socio-demographic characteristics*
Locomotion - Spatial Behavior	*trajectories, walking speed, group proxemics*

Table 4.1: *A synthetic description of the proposed methodology for the unobtrusive observation of pedestrian circulation dynamics in urban crowded scenarios (considering both data collection and analysis).*

4.3 In Vitro Experiment

From the social science perspective, this methodology permits to collect empirical data about human behavior, measuring the impact of a manipulated stimulus event (i.e. *independent variable*) on subject's behavior (i.e. *dependent variable*) in terms of occurrence, magnitude and persistence (Schinka et al., 2003). In particular, experiments are aimed at verifying and demonstrate the validity of an a priori hypothesis about the cause-effect relation between the independent and dependent variables, by means of standard and replicable procedures performed in controlled laboratory settings.

Experiments typically follow the protocol of clinical trials (with the exception of the so called *quasi-experiment*, in which the experimenter does not manipulate the independent variable and not even sample participants) (Goodwin, 2009): participants are sampled and randomly assigned to the treatment condition (exposing them to the independent variable) or control condition (no treatment), in order to compare results (i.e. experimental procedure *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*). The collected data are analyzed by means of statistical tests, in order to evaluate the significance of results (i.e. *internal validity*) and the possibility to generalize them to the overall population (i.e. *external validity*).

Contrary to the observational methodology, experiments are performed in laboratory settings in order to exert the maximum amount of control over the environment in which the study takes place (i.e. *nuisance variables*). For this reason, one of the most critical aspects in performing experiments about human behavior is related to the limited possibility to extend the results achieved in an artificial setting to natural contexts (Pashler and Yantis, 2004).

4.3.1 Experimental Investigation of Locomotion and Spatial Behavior

This Section presents the application of the experimental method for the investigation of human locomotion-spatial behavior in laboratory settings, focusing on both data collection (e.g., hypothesis, sample, experimental setting, procedure, authorization) and data analysis (e.g., level of service, trajectories, walking speed, personal space, crowding, group spatial layout).

Data Collection

Due to the complexity of the overall phenomenon, several practical factors has to be considered in order to design and perform experimental investigation of locomotion and spatial behavior, with particular reference to: variables and hypothesis, sample, experimental setting, procedure and authorizations required to carry out the survey.

- *Hypothesis*: the experimental hypothesis has to be clearly stated, considering the supposed impact of the manipulated independent variable (e.g., level of density, physical features of the walking path) on the dependent variable (e.g., subject's locomotion and spatial behavior);

- *Sample*: participants are sampled considering the socio-demographic characteristics of the overall population of interest and some requirements that are needed in relation to procedure itself. The experimental investigation of grouping can be performed by participating subjects spontaneously organized in natural groups (decreasing external validity) or managing them in artificial groups (decreasing internal validity);

- *Experimental Setting*: any nuisance variable is controlled in order to avoid interferences on results (e.g., lighting, temperature, noise, people talking). The setting is arranged with professional equipments for data collection (e.g., full HD cameras and tripods for video footages, checklists and worksheets for taking notes). During testing only the experimenter and confederates are in the experimental room at any given time;

- *Procedure*: the experimental protocol consists of a controlled, standard and replicable procedure. It can be performed between subjects or within subjects. The duration time and the order of execution of the procedures have to be planned in order to avoid the interference of any tiring and learning effects on results. The procedure has to be briefly introduced to participants before its execution.

- *Authorization*: the experimental investigation of human behavioral outcomes in laboratory setting potentially include several stressful or harmful factors related to the procedure itself. For this reason, it is needed to obtain the official authorization of the ethic committee of the institution that promotes the survey (e.g., University Ethic Committee). The existing legislation about privacy has to be consulted and complied in order to respect some ethical issues about the privacy of the people involved in the study, also considering the necessity to obtain their informed consent beforehand.

Data Analysis

The experimental investigation of human locomotion-spatial behavior is based on microscopic indicators about locomotion (e.g., level of service, trajectories, walking speed) and proxemics (e.g., personal space, crowding, group spatial layout). Data analysis can be performed manually or by using automatic computer-based techniques.

- *Locomotion Behavior*: this consists on investigating the impact of the physical features of the setting (e.g., walking path, presence of turing angles and/or obstacles) on human locomotion behavior, considering both individual and group levels of investigation: level of service, trajectories, walking speed, pedestrian competitive interactions in situation of high density;

- *Spatial Behavior*: this consists on investigating proxemic behavior during locomotion (considering both individual and group levels of investigation): dynamic regulation of interpersonal distances, size and shape of personal space, proxemic behavior of walking groups, physiological and psychological stressful reaction to high density situations.

4.4 In Silico Simulation

The use of simulations represents an innovative methodology that permits to reproduce and investigate physical or abstract complex systems (e.g., natural system, network traffic) by means of computer-based software platforms (Gilbert and Troitzsch, 2005).

Experimental Investigation of Human Locomotion and Spatial Behavior	
Data Collection	
Hypothesis	*cause-effect relation between variables*
Experimental Setting	*control over nuisance variables, equipment*
Sample	*representativeness*
Procedure	*standard protocol, treatment-control condition, pre-post tests*
Authorization	*ethics committee permission, participants' consent*
Data Analysis	
Locomotion Behavior	*level of service, trajectories, walking speed, grouping*
Spatial Behavior	*personal space, crowding, group proxemics*

Table 4.2: *A synthetic description of the proposed methodology for the experimental investigations of human locomotion and spatial behavior in laboratory setting (considering both data collection and analysis).*

In order to perform and finalize simulations it is necessary to (*i*) develop a formal and computational model, in order to represent the features/functions of each component that comprises the system and their mutual interaction, and (*ii*) to validate the model by means of empirical evidences collected in real case scenarios, improving its expressiveness and efficiency in reproducing the phenomenon.

There are some objections about the simplified level of correspondence between computer-based simulations and complex social systems (Federici et al., 2006). However, the main contribution of this methodology is based on the possibility to envision those phenomena that are difficult to be directly observed in real scenarios. Moreover, simulations permit to perform *in-machina* experiments focused on alternative conditions and courses of action (i.e. *what-if scenarios*) and to produce a series of statistical data that can support the understanding of the phenomenon from a different level of abstraction.

4.4.1 Simulation of Pedestrian Crowd Dynamics

The use of computer-based simulation platforms (e.g., Freewalk, Vissim, Legion, Exodus, MASSEgress) permits to provide applicative solutions to support the management of pedestrian crowd dynamics. The issue of defining formal computational models has been tackled from different perspectives, depending on the definition of the phenomenon (Shiwakoti et al., 2008):

- *Macroscopic approach*: this is focused on the aggregate representation of pedestrian crowd dynamics (e.g., pedestrian flows, level of density and walking speed). The phenomenon is modeled without considering human behavior;

- *Microscopic approach*: this is focused on the definition of pedestrians as single elements occupying a certain space at a certain time. This kind of models are based on the assumption that pedestrians move towards their destination according to social interactions and the physical features of the environment.

According to Manenti (2013), pedestrian crowd modeling approaches differ among them considering the representation of pedestrians as: *particles* (physical approach, pedestrians are considered as particles subject to forces), *cells* (Cellular Automata approach, pedestrians are considered as occupied states of the cells) or *agents* (agent-based approach, pedestrians are represented as autonomous and situated entities).

- *Pedestrian as particles*: this approach is based on the representation of pedestrians as particles subject to forces, in analogy with fluid dynamics. In particular, the social force model (Helbing and Molnar, 1995; Helbing, 2001) represents pedestrian crowd dynamics as mediated by: forces of attraction, leading pedestrians/particles towards their destinations, and forces of repulsion, representing the tendency of pedestrians to stay at a certain distance from other points of the environment;

- *Pedestrians as cells*: coming from traffic models, Cellular Automata (CA) approach represents the simulated environment and the entities it comprises in a discrete way, by means of space-time steps (Schadschneider et al., 2002). Every cell has an own state that indicates if the site is occupied by a pedestrian or by an obstacles. Pedestrian interactions are based on the *floor field* method: a virtual traces that influence pedestrian transitions and movements, by means of the predefined desirability associated to each cell (Nishinari et al., 2004);

- *Pedestrians as agents*: in analogy with CA approach, the agent-based approach exploits a cellular space in order to represent the spatial scenario in which a system of autonomous entities moves according to a set of rules (Ferber, 1999). This approach is an interesting alternative to physical and discrete approaches, thanks to the possibility to represents heterogeneous situated agents that encapsulate different behavioral specifications. Agents are also able to perceive and interact among them, as well as the environment itself (Batty, 2003; Bandini et al., 2007).

4.4.2 The Simulation Platform MAKKSim

The empirical investigation of pedestrian circulation dynamics and human locomotion-spatial behavior is aimed at validating the simulation platform MAKKSim, developed by the Complex Systems and Artificial Intelligence research center of the University of Milano-Bicocca (Bandini et al., 2001, 2009), in terms of its expressiveness and efficiency in simulating pedestrian crowd dynamics.

The modeling approach that sets MAKKSim starts from the definition of crowds as complex systems, that comprise many interacting parts with the ability to generate emergent collective behavior (not readily predictable or even completely deterministic) (Meyers and Kokol, 2009). In particular, the agent-based model of MAKKSim represents pedestrians as multiple and heterogeneous agents, characterized by perceptive and behavioral specifications (e.g., perceive and avoid spatial elements that represent obstacles, follow paths throughout environmental elements and perceive other agents) and the capability to interact in the shared environment in order to achieve some individual or collective goals (Bandini et al., 2004).

According to the growing interest in modeling pedestrian crowd dynamics as influenced by the presence of groups (Klingsch, 2010; Moussaïd et al., 2010), the model of MAKKSim represents groups as sets of pedestrians that mutually recognize their membership and move following two behavioral rules (Manenti et al., 2011, 2012):

- *goal-driven behavior*: each agent moves towards its target and, in the same way, every group moves to the shared goal among the members;
- *proxemic-driven behavior*: every agent dynamically regulate the spatial distances among the others and, in the same way, every group is driven by the tendency to maintain spatial cohesion during locomotion.

Modeling and Simulation of Pedestrian Crowd Dynamics	
Classification	
Macroscopic Approach	*aggregate representation (flow, density and speed)*
Microscopic Approach	*interactions among pedestrians and the environment*
Pedestrian as Particles	*particles subject to forces*
Pedestrian as Cells	*occupied states of the cells*
Pedestrian as Agents	*autonomous agents situated in the environment*
MAKKSim Simulation Platform	
Grouping	*agents can recognize those that belong to their group*
Goal-driven Behavior	*moving toward the target (group shared target)*
Proxemic-driven Behavior	*dynamics regulation of spatial distances (group cohesion)*

Table 4.3: *A synthetic description of the different approaches in modeling pedestrian crowd dynamics, and the functionalities of the agent-based computational model that sets the simulation platform MAKKSim.*

4.5 Final Remarks

The empirical investigation of pedestrian crowd dynamics requires an interdisciplinary approach, considering the variety of relevant knowledge and skills for supporting data collection. The methodological approach that sets the thesis work can be synthetically defined as a virtuous cycle (see in Fig.4.1) composed of: *in vivo* observations of pedestrian circulation dynamics in urban crowded scenarios, *in vitro* experimental investigation of human locomotion-spatial behavior in laboratory setting, *in silico* simulation of pedestrian crowd what-if scenarios.

In this respect, the Chapter proposed a comprehensive overview of each method, considering its specific contribution for both data collection and analysis (e.g., crowd estimation, crowd composition, crowd profiling, human locomotion-spatial behavior). Moreover, the contribution coming from the use of pedestrian crowd simulations is synthetically presented in the second part of the Chapter, with reference to different modeling approaches (e.g., pedestrians as particles, cells and agents). Thanks to the collaboration with the CSAI research centre, the proposed methodology is finally aimed at validating the simulation platform MAKKSim and collecting further empirical data by means of in silico simulations of pedestrian crowd dynamics.

5

In Vivo Observation of Pedestrian Circulation Dynamics

The Chapter presents the results achieved by means of the unobtrusive observation of pedestrian circulation dynamics in two urban crowded scenarios: the Campus of the University of Milano-Bicocca (Italy) and the Vittorio Emanuele II gallery (Milan, Italy), respectively presented in Section 5.2 and Section 5.3. According to the proposed methodological approach, data collection and analysis were carried out focusing on the impact of density, proxemics and grouping on the overall phenomenon. The achieved results (e.g., level of density and service, pedestrian flows composition, group spatial arrangement and dispersion, trajectories, walking speed) represent an useful contribution towards the definition of descriptive sets of metrics and parameters for characterizing pedestrian crowd dynamics and supporting the validation of in silico simulations.

5.1 Introduction

This Chapter presents several empirical studies aimed at investigating pedestrian circulation dynamics in urban crowded scenarios. In particular, two unobtrusive observations were carried out, focusing on the impact of density, proxemics and grouping on the overall phenomenon. The Chapter includes the results achieved by means of: (*i*) the observation of the pedestrian flows oncoming to the Campus of the University of Milano-Bicocca (Milan, Italy) in order to participate to the admission test of the Faculty of Psychology (September 1st, 2011), (*ii*) the observation of the pedestrian flows at the Vittorio Emanuele II gallery, a commercial-touristic walkway situated in the Milan city center (Italy) (November 24th, 2012).

According to the methodological approach that sets the thesis work, data collection and analysis were carried out considering both macroscopic and microscopic indicators for describing and evaluating pedestrian crowd dynamics (as described in 4), such as: level of density and service in the environment (i.e. crowd estimation), presence of groups in the streaming of passersby (i.e. crowd composition), socio-demographic characteristics of the observed population (i.e. crowd profiling), proxemic spatial arrangement and dispersion of walking groups, trajectories and walking speed of both single pedestrians and group members (i.e. human locomotion-spatial behavior).

The observed urban scenarios are presented in Section 5.2 and Section 5.3. The achieved results are respectively presented in Section 5.2.2 and 5.3.2. The chapter ends with final remarks about the collected empirical evidences and their employment towards the definition of descriptive set of metrics and parameters for characterizing pedestrian crowd dynamics. This was finally aimed at supporting the design of experimental investigations about the phenomenon and the validation of computer-based modeling and simulations.

5.2 The Admission Test of the University of Milano-Bicocca

This Section presents the empirical results achieved by means of the unobtrusive observation of the pedestrian flows oncoming to the Campus of the University of Milano-Bicocca (Milan, Italy), in order to participate to the admission test of the Faculty of Psychology on September 1st, 2011. The survey consisted of people counting activities and video footages, focused on the pedestrian circulation dynamics at Piazza dell'Ateneo Nuovo before the opening time of the examination and during the entrance process to the Buildings U6 and U7 (the venues in which participants had to attend the test) (as illustrated in Fig. 5.1).

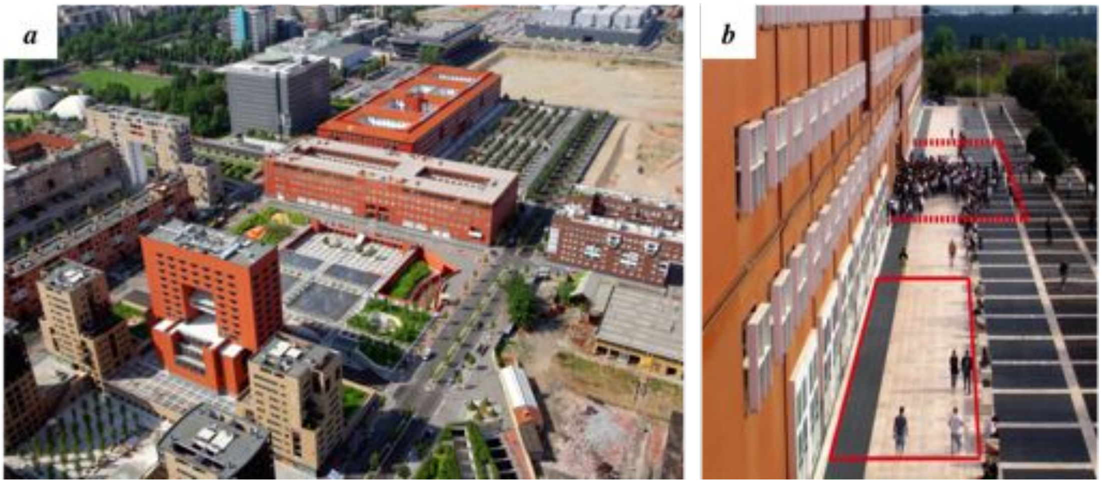

Figure 5.1: *The aerial of the Campus of the University of Milano-Bicocca (a) and Piazza dell'Ateneo Nuovo (b), with focus on the observed portion of the walkway and the waiting area in front of the Building U6 (highlighted with continuous and dashed red lines).*

5.2.1 Observational Setting

The chosen scenario represents an optimal case study thanks to the large amount of people that participate every year to the admission test[1]. Several preliminary inspections permitted to identify different locations for positioning the equipment for video footages from a zenith point of view (in order to limit video images distortion and trajectories occlusion) and from hidden locations (in order to not influence the subjects' behavior) (as illustrated in Fig. 5.2):

- Location A: the mezzanine bridge that connects the 3^{rd} floor of the Buildings U6 and U7. Considering the public transport services situated nearby the Campus (Greco Pirelli train station, bus and tram stops), this location allowed to observe almost the total number of the oncoming pedestrians to Piazza dell'Ateneo Nuovo;
- Location B/C: the lecture hall of the Faculty of Psychology on the 3^{rd} floor of the Building U6 and the common area on the 1^{st} floor of the Building U6. These locations permitted to observed the entrance process to the Building U6, with reference to the waiting area at Piazza dell'Ateneo Nuovo and the area in front of the gate B (see Fig. 5.1/b and Fig. 5.4);
- Location D: the Computer Lab 732 on the 3^{rd} floor of the Building U7. This location permitted to observe the waiting area in front of the Buildings U6 and a selected portion of the walkway at Piazza dell'Ateneo Nuovo (as illustrated in Fig. 5.1/b).

The observation was carried out on September 1st 2011, from 7:30 am to 10:00 am. The staff involved in performing the survey was composed by two supervisors and six confederates distributed at different locations. The equipment for video footages consisted of four full HD video cameras with tripods. Each observer was equipped with an head-counting device, chronograph and worksheets for data entering. The manual analysis of the recorded video images was performed by using *VLC* media player, thanks to the possibility to playback the images in slow motion and/or frame by frame and to use an extension time format that included hundreds of a seconds.

5.2.2 Results

First, data analysis was aimed at comparing the results achieved by means of on site people counting activities (performed from locations A and D) and the analysis of the video recorded images, in order to cross-check errors. Results showed that, even if expert counters were employed during the on site counting activities, an over

[1]Thanks to the collaboration with the Authorities of the University of Milano-Bicocca it was possible to consult beforehand the list of the enrolled participants to the admission test: 2094 people, including 437 males (29%) and 1657 females (79%), with an average age of 19 years old.

estimation error in determining the total number of pedestrians (about 4%) and the pedestrian flows composition in terms of groups (about 10%) was detected. For this reason, data analysis was performed relying on the recorded video images, guarantying more accuracy and reducing errors.

Figure 5.2: *The map of the aerial of Piazza dell'Ateneo Nuovo (from Google Maps), with particular reference to the walking path to reach Piazza dell'Ateneo Nuovo from the public transport services situated nearby the Campus (highlighted with a dashed red line) and the locations A, B/C, D for video footages.*

Flow Composition

This Section is focused on the composition of the pedestrian flows oncoming to Piazza dell'Ateneo Nuovo (location A), with reference to total number of pedestrians and the presence of groups in the streaming of passersby (e.g., couples, triples and groups of four members). Results showed that No. 1897 people passed through Viale dell'Innovazione in order to reach the Piazza dell'Ateneo Nuovo and the entries of the Buildings U6 and U7. As illustrated in Figure 5.3, the observed pedestrian flows assumed a cyclical up-down pick levels pattern, due to the presence of public transport services situated nearby the Campus of the University of Milano-Bicocca, that periodically discharged passengers.

Results showed that the 34% of the observed subjects arrived alone, while the 66% of them arrived in groups: 77% couples, 19% triples and 4% larger groups composed of four members. The identification of groups was assessed on the basis of verbal and nonverbal communication among members (e.g., visual contact, body orientation, gesticulation and spatial cohesion among members). To more thoroughly evaluate all these indicators the coder was actually encouraged to rewind the video and take the necessary time to tell situations of local similar movements from actual group members.

Group Spatial Arrangement

This Section is focused on the proxemic arrangement of walking groups (e.g., couples, triples and groups of four members), related to the pedestrian flows oncoming to Piazza dell'Ateneo Nuovo (location A). In order to perform data analysis, the coder was asked to rewind the video images in order to detect the most frequent spatial layout of each group. Results as follow:

- 97% of couples was characterized by a line abreast pattern, 3% by a river-like pattern;
- 66% of triples walked with a line abreast pattern, 33% with a V-like pattern and 1% with a river-like pattern;
- groups with four members split into sub-units of dyads, triads, and single individuals: 30% of four-person groups was characterized by rhombus-like pattern (one person heading the group, followed by a dyad and ended by an another single person), 21% of the groups split into two dyads, 21% walked with a line abreast pattern, 14% triads followed by a single person, 7% single individual followed by a triad, 7% by V-like pattern.

Level of Density and Service

This Section presents the results achieved by means of the analysis of the level density in the observed scenario, with particular reference to the pedestrian flows oncoming to the entry of the Building U6 at Piazza dell'Ateneo Nuovo (location D). No. 745 people (representing the 39% of the total number of the observed pedestrian oncoming to Piazza dell'Ateneo Nuovo) walked through the path from 7:52 am to 8:15 am. Considering the physical features of the selected portion of the walkway (24 m long, 6.1 m width, 146.4 squared/meter, as illustrated in 5.1/b), results showed the observed scenarios was characterized by a low level of density (0.18 people per squared meter).

According to the Highway Capacity Manual (Milazzo II et al., 1999) and the level of service criteria (LOS) (Fruin, 1971), the level of density in the observed scenario was more properly estimated by counting the number of people walking through a certain unit of space (meter) in a certain unit of time (minute). Results (see Table 6.1) showed that the average level of service (5.09 pedestrian/minute/meter) belonged to LOS A (free flow in situation of low density), with several time intervals belonging to LOS B (irregular flow in condition low-medium density).

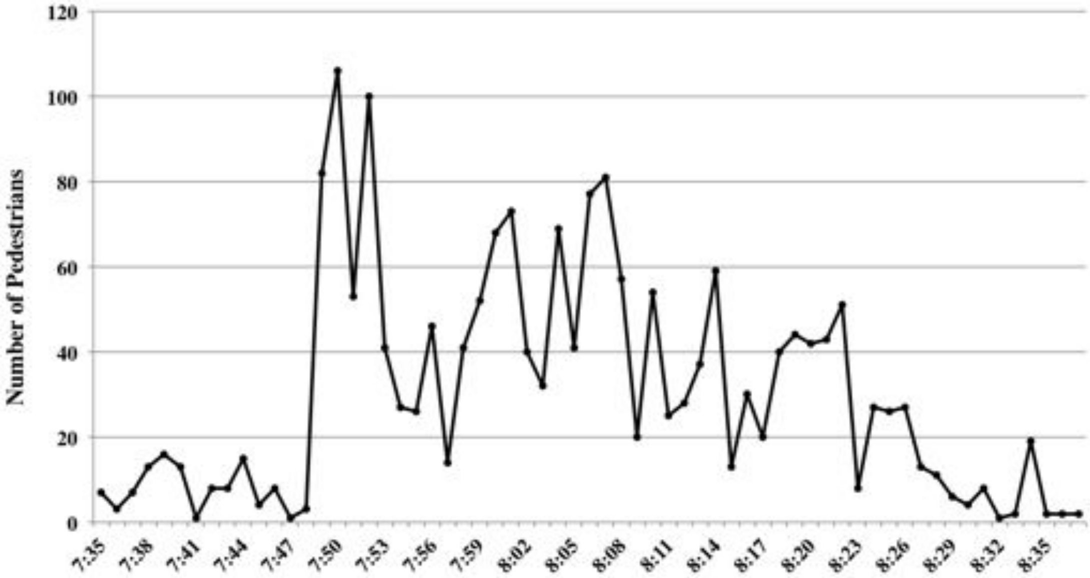

Figure 5.3: *The time distribution of the observed pedestrian flows oncoming to Piazza dell'Ateneo Nuovo. The X-axis refers to the duration time of the performed video footages (from 7:35 am to 8:40 am, until the observed pedestrians reached the waiting areas in front of the Building U6 and U7).*

Walking Speed

This Section is focused on the walking speed of both single pedestrians and group members (location C) (related to the selected portion of the walkway in front of the Building U6, as illustrated in Fig. 5.1/b). In order to focus on low-medium density, we considered the recorded video images related to LOS$\geq$6 pedestrian/minute/meter. No. 201 pedestrians were taken into account (134 females and 67 males, 27% of the total pedestrian flows oncoming to the entry of the Building U6), composed of: 50 single pedestrians (25%), 50 couples (50%) and 17 triples (25%) (larger groups were not regularly detected).

The results achieved by means of an oneway analysis of variance (i.e. ANOVA) showed a significant difference (p value$<$0.05) among the walking speed of single pedestrians (1.38 m/s, sd 0.16), couples (1.30 m/s, sd 0.15) and triples (1.21 m/s, sd 0.12). Two tailed t-test analyses showed a significant difference (p value$<$0.01) between the walking speed of singles and couples, singles and triples, couples and triples. Further two tailed t-test analyses were focused on checking the impact of gender on walking speed. Results showed no significant differences (p value$>$0.05) between the average walking speed of: single females (1.38 m/s, sd 0.16) and males (1.39 m/s,

Time Distribution	Pedestrian Flow	Pedestrian Flow Rate	Level of Service
07:52	7	1.15 (ped/min/m)	*A*
07:53	24	3.93 (ped/min/m)	*A*
07:54	31	5.08 (ped/min/m)	*A*
07:55	40	6.56 (ped/min/m)	*A*
07:56	69	11.31 (ped/min/m)	*B*
07:57	24	3.93 (ped/min/m)	*A*
07:58	28	4.59 (ped/min/m)	*A*
07:59	24	3.93 (ped/min/m)	*A*
08:00	15	2.46 (ped/min/m)	*A*
08:01	17	2.79 (ped/min/m)	*A*
08:02	16	2.62 (ped/min/m)	*A*
08:03	26	4.26 (ped/min/m)	*A*
08:04	38	6.23 (ped/min/m)	*A*
08:05	55	9.02 (ped/min/m)	*B*
08:06	27	4.43 (ped/min/m)	*A*
08:07	37	6.07 (ped/min/m)	*A*
08:08	33	5.41 (ped/min/m)	*A*
08:09	52	8.52 (ped/min/m)	*B*
08:10	50	8.20 (ped/min/m)	*B*
08:11	34	5.57 (ped/min/m)	*A*
08:12	19	3.11 (ped/min/m)	*A*
08:13	36	5.90 (ped/min/m)	*A*
08:14	17	2.79 (ped/min/m)	*A*
08:15	26	4.26 (ped/min/m)	*A*

Table 5.1: *The time distribution of the pedestrian flows oncoming to the entry of the Building U6 (from 07.52 am to 8.15 am), with reference to the flow rate and level of service estimated in the observed scenario.*

sd 0.17), same gender couples (1.28 m/s, sd 0.26) and mixed-gender couples (1.32 m/s, 0.13), same gender triples (1.20 m/s, sd 0.12) and mixed-gender triples (1.16 m/s, sd 0.11). Considering the differences in group spatial arrangement, two tailed t-test analyses showed no significant difference (p value>0.05) between the average speed of groups walking with line abreast pattern (1.27 m/s, sd 0.13) and V-like patterns (1.14 m/s, sd 0.10). In conclusion, results showed that in low-medium density situations group members (including couples, triples) walked 9% slower than single pedestrians.

Entrance Process to the Building U6

This Section presents the results achieved by means of the analysis of the entrance process to the Building U6 (that was managed by the security service of the University of Milano-Bicocca by grouping participants and calling them to enter the building). Results showed a maximum pick level of density (4.43 people per squared meter) at

9:22 am in the area in front of the gate B (6.54 m long, 4.7 m width, 30.7 squared meter, as illustrated in Fig. 5.4) before the opening time of the examination. The level of service was estimated by counting the number of people entering the Building U6 (No. 663 people) by using the gate B (6.25 m width). Results showed an average LOS C (28.54 pedestrian/minute/meter), that is associated with an irregular pedestrian flow in condition medium density (see Fig.5.5).

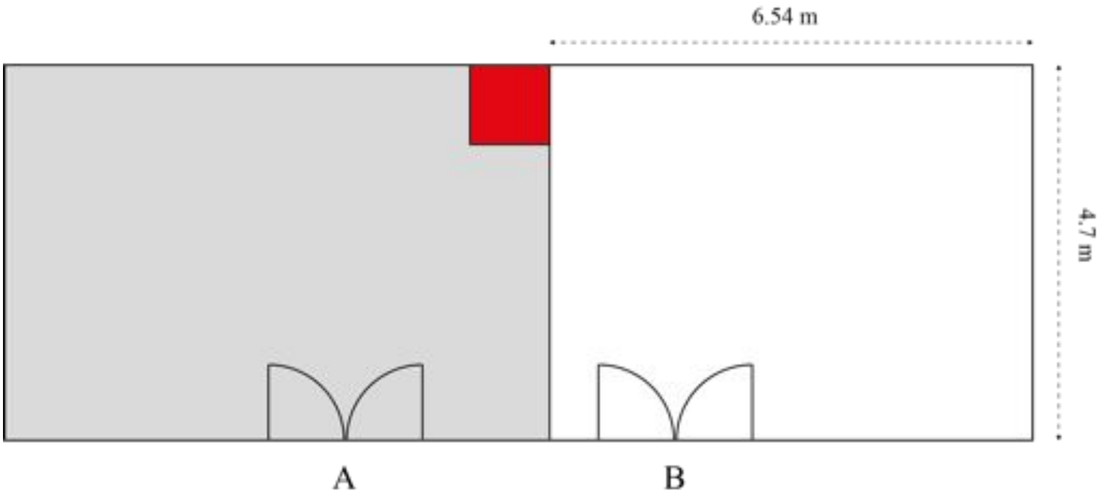

Figure 5.4: *A schematic representation of the physical features of the entry of the Building U6, with particular reference to waiting area situated in front of the gate B.*

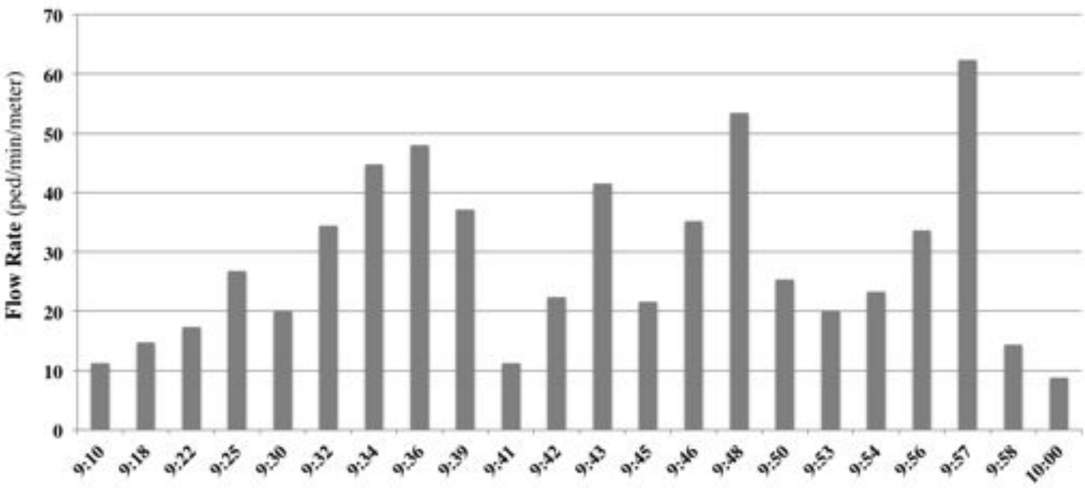

Figure 5.5: *The time distribution of the flow rate related to the total number of pedestrians passing trough the Gate B of the Building U6. The X-axis refers to the duration time of the performed video footages (from 9:12 am and to 10:02 am).*

5.3 The Vittorio Emanuele II Gallery

This Section is aimed at presenting the results achieved by means of the unobtrusive observation of the pedestrian circulation dynamics at the Vittorio Emanuele II gallery, a popular commercial-touristic walkway situated in the Milan city center (Italy). The survey was performed on the 24th of November 2012 (on Saturday afternoon).

Figure 5.6: *As illustrated form the left to the right side: an overview of the pedestrian circulation dynamics at the Vittorio Emanuele II gallery (Milan, Italy) (a) and the aerial of the walkway within the gallery (b).*

5.3.1 Observational Setting

The Vittorio Emanuele II gallery represents an optimal scenario for the observation of pedestrian crowd dynamics, given the large amount of people that pass through the gallery during the weekend for shopping, entertainment and visiting touristic-historical attractions (as illustrated in Figure 5.6). The equipment for video footages was positioned on a balcony that surrounds the inside volume of the gallery from about ten meters in height. This permitted to achieve a zenith point of view of the setting (limiting video image distortion and trajectories occlusion) and to not influence subjects' behavior (thanks to a railing of the balcony partly hiding cameras).

The geometric decorated pavement of the walkway permitted to fix some spatial reference points in order to analyze data considering the inclined perspective of the camera. The steel-glass roof that covers the entire volume of the gallery permitted to prevent that, in case of a rainy day, the presence of umbrellas would occluded pedestrians, compromising the success of the survey.

The observation was carried out on the 24^{th} of November 2012 (from about 2:50 pm to 4:10 pm). The staff performing the survey was composed of one supervisor and three confederates. The equipment for video footage consisted of two full HD video cameras with tripods. A squared portion of the walkway was considered for data analysis: 12.8 meters wide and 12.8 meters long (163.84 squared meters).

In order to perform data analyses the inner space of the selected area were discretized in cells by superimposing a grid on the video images (see Fig. 5.7). In particular, the grid was designed as composed of No. 1024 squared cells (0.4 meters wide and 0.4 meters long) by using *Adobe Photoshop CS5*. Then. it was inclined according to the perspective of the video images and set up with an alphanumeric code on the sides (from 1 to 32 on both left and right sides, from A to Ff on both top and bottom sides). Lastly, the grid with a transparent background was superimposed to a black-white version of the video images by using *iMovie 2011 (9.0)*. The analysis of the video images was performed by using *VLC media player*, thanks to the possibility to playback the images in slow motion and/or frame by frame and to use an extension time format that included hundreds of a seconds.

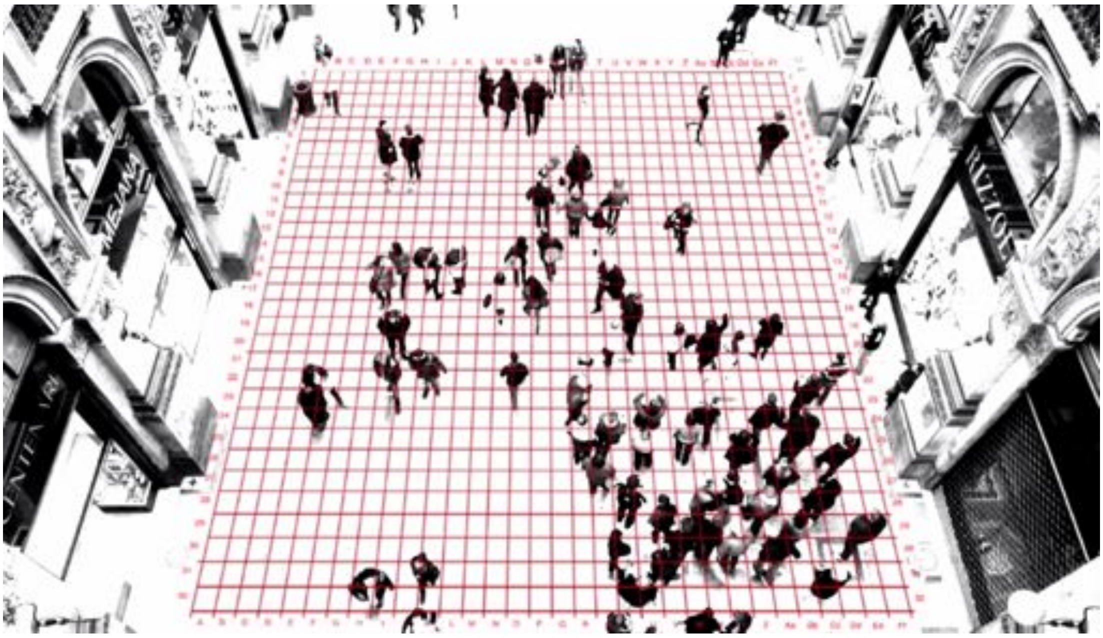

Figure 5.7: *A snapshot from the recorded video images related to the pedestrian circulation dynamics at the Vittorio Emanuele II gallery, with particular reference to the superimposed alphanumeric grid used for data analysis.*

5.3.2 Results

Data analysis was performed relying on the recorded video images. Results comprehend both macroscopic and microscopic metrics for evaluating the impact of proxemics, grouping and density on pedestrian circulation dynamics, such as: the level of density and service in the environment, pedestrian flow composition in terms of groups, proxemic spatial arrangement and dispersion of walking groups, trajectories and walking speed of both single pedestrians and group members.

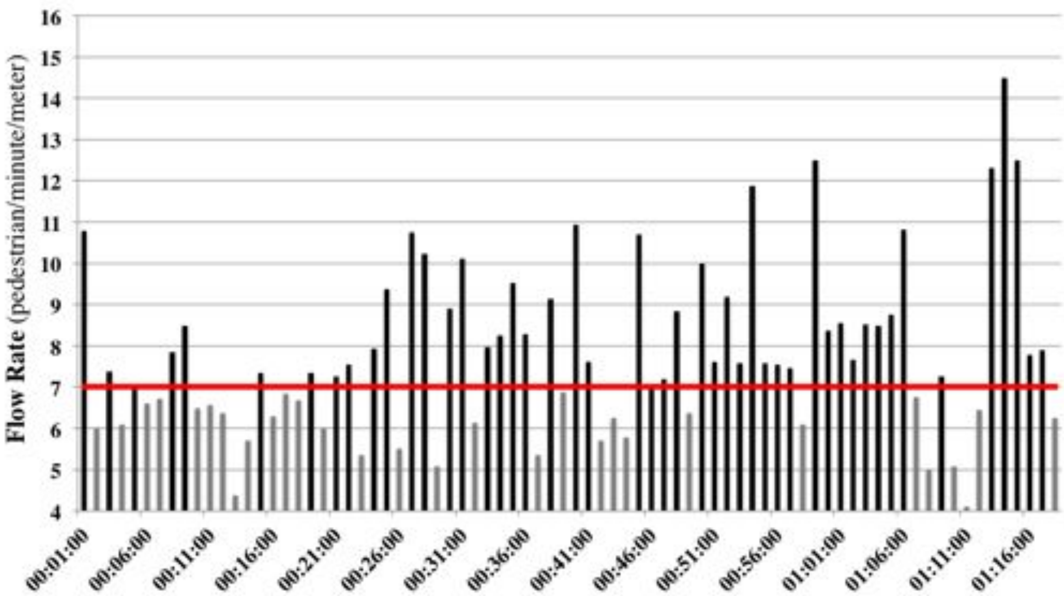

Figure 5.8: *The time distribution of the flow rate observed at the Vittorio Emanuele II gallery. The 41% of the minutes corresponded to LOS A (light grey colored), the 59% corresponded to LOS B (black colored). The average LOS B is highlighted with a red colored horizontal line. The minute 00:00:00 reported X-axis refers to the starting time of the observation (2:50 pm).*

Level of Density and Service

This Section presents the results achieved by means of the analysis of the average level of density within the observed portion of the Vittorio Emanuele II gallery. Data analysis was focused on a selection of 78 snapshots extracted from the recorded video images (considering the starting time of each minute of the video). Due to the huge available space within the walkway, the observed level of density was low (0.22 people per squared meter). However, several medium-high density situations were detected considering large groups of tourists, but also occasional local situations in which smaller groups moving in opposite directions were situated in the same side of the walkway.

In accordance to the Highway Capacity Manual (Milazzo II et al., 1999) and the level of service criteria (Fruin, 1971), the level of density in the observed scenario was more properly estimated by counting the number of people walking through a certain unit of space (meter) in a certain unit of time (minute). The bidirectional pedestrian flows (from North to South and vice versa) were manually counted minute by minute: No. 7773 people passed through the selected portion of the walkway from 2:50 pm to 4:08 pm. The average level of flow rate (7.78 ped/min/m) within the observed scenario belonged to LOS *B* (as illustrated in Fig. 5.8), that is associated with irregular flows in condition low-medium density. The observed cyclical up-down pick levels pattern is related to several public transport services situated nearby the gallery, that periodically discharged passengers.

Moreover, the collected data are characterized by a down peak level between the minute 01:08:00 and 01:12:00, due to an unexpected flash mob that happened suddenly within the gallery (see Fig. 5.8). This event gathered a crowd of spectators looking at a crew of young performers, reducing the pedestrian flows directed towards the exits of the gallery. After the flash mob ended, the observed pedestrian flows registered a high peak level (between the minute 01:13:00 and 01:15:00), due to the spectators moved towards the exits of the walkway at the same time. However, this study is not focused on this phenomenon, since the portion of the environment in which it took place was out of the observed area.

Flow Composition

This Section is focused on the pedestrian flows composition, with reference to the presence of groups. The identification of groups in the streaming of passersby was assessed on the basis of verbal and nonverbal communication among members (e.g., visual contact, body orientation, gesticulation and spatial cohesion among members). To more thoroughly evaluate all these indicators the coder was actually encouraged to rewind the video and take the necessary time to tell situations of simple local similar movements by different pedestrians from actual group situations.

A subset of 15 minutes was extracted sampling the video one minute every five: 1645 pedestrians were manually counted (21.16% of the total bidirectional flows). Results showed that the 15.81% of the observed pedestrians walked alone, while the 84.19% walked in groups, as composed of 43.65% of couples, 17.14% triples and 23.40% four members groups. The observed large structured groups, such as touristic committees, were analyzed considering sub-groups.

Group Spatial Arrangement

This Section is focused on the spatial arrangement of walking groups (with reference to the previously described sample). In order to perform data analysis, the coder was asked to rewind the video and to take the necessary time to tell the most frequent spatial layout of each group while walking trough the path. Results about group proxemics spatial arrangement showed that:

- 94.43% of couples walked with a line abreast pattern, while 5.57% walked with a river-like pattern;
- 31.91% of triples were characterized by line abreast pattern, 9.57% by river-like pattern and 58.51% by V-like pattern;
- 29.61% of groups of four members were characterized by line-abreast pattern, 3.19% by river-like pattern, 10.39% by V-like pattern, 10.39% triads followed by a single person, 6.23% single individual followed by a triad, 7.79% rhombus-like pattern (one person heading the group, followed by a dyad and a single person), 32.47% of the groups split into two dyads.

Walking Path and Speed

This Section presents the results achieved by means of the analysis of the walking path and speed of both singles and group members. Data analysis consisted of measuring the trajectories of each sampled pedestrian and the needed time to pass through the monitored portion of gallery (considering the area in between the first and last rows of the alphanumeric grid). In order to focus on low-medium density situations, data analysis was focused on the minutes characterized by LOS B. A sample of No. 122 people was considered for data analysis, as composed of: 30 singles, 15 couples, 10 triples and 8 groups of four members. Pedestrians who stopped or slowed to take pictures or shopping were not taking into account. The estimate age of the sampled pedestrians (56% males and 44% females) was approximately between 15 and 70 years. Groups with accompanied children were not taken into account for data analysis. Differences in age and gender were not considered in this study.

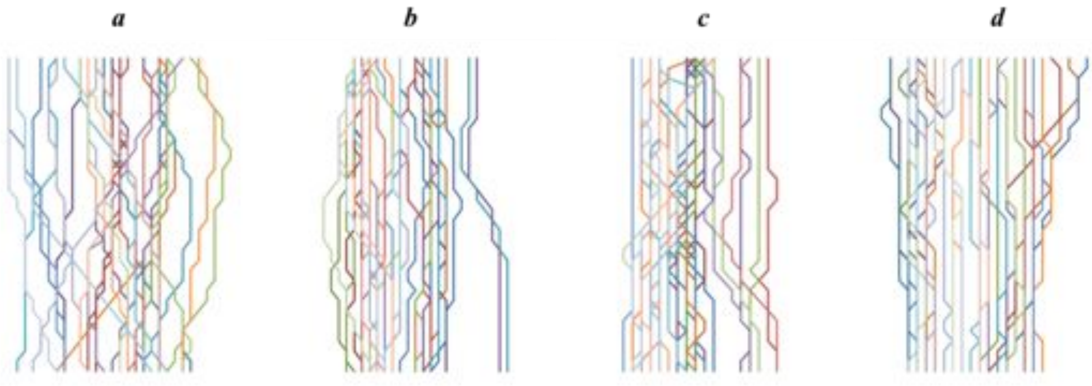

Figure 5.9: *As illustrated from the left to the right side, the trajectories of the observed pedestrians (estimated by using the alphanumeric grid), with reference to (a) singles, (b) couples, (c) triples and (d) groups of four members.*

15° SINGLE (Male) - Minute 00.58.00/00.59.00

Starting Time 58.33,428					
Position	S,32	T,31	T,30	T,29	....
Direction	-	North Est	North	North	....
Path	0.2 m	0.56 m	0.4 m	0.4 m	....

Figure 5.10: *The worksheet used to track the trajectories of pedestrians within the observed portion of the walkway by means of the alphanumeric grid. In particular, the coder was asked to note the starting time, the actual position (the occupied cell), the direction (cardinal point) and the length of the path of each subjects (considering the position of each cell).*

The alphanumeric grid was used to track the trajectories of both single and group members within the walkway and to measure the length of their path[2] (considering the features of the cells: 0.4 m wide, 0.4 m long). Two tailed t-test analyses were used to identify differences among the average walking path of singles (13.96 m, sd 1.11), couples (13.39 m, sd 0.38), triples (13.34 m, sd 0.27) and groups of four members (13.16 m, sd 0.46) (as illustrated in Fig. 5.9).

Results showed a significant difference (p value$<$0.05) between the walking path of singles and couples, singles and triples, singles and groups of four members. No significant differences (p value$>$0.05) between the walking path of couples and triples, triples and groups of four members, couples and groups of four members. In conclusion, results showed that the path of singles was 4% longer than the path of group members (including couples, triples and groups of four members) (see Fig. 5.9).

The walking speed of both singles and group members was detected considering the path of each pedestrian and the time to walk through the monitored portion of the gallery (delimited by using the alphanumeric grid). Two tailed t-test analyses were used to identify differences among the walking speed of singles (1.22 m/s, sd 1.16), couples (0.92 m/s, sd 0.18), triples (0.73 m/s, sd 0.10) and groups of four members (0.65 m/s, sd 0.04). Results (see Fig. 5.11) showed a significant difference (p value$<$0.01) in walking speed between singles and couples, singles and triples, singles and groups

[2]To measure the walking path of the sample pedestrians, each subject was considered as a point without mass in a two-dimensional plane. By using the alphanumeric grid, we considered the cell occupied by the feet of each pedestrian as its own actual position. Every straight step was measured as the segment between the center of two cells (0.4 m long path). Any oblique step cell by cell was measured as the diagonal between the two cells (0.56 m long path). The starting and final steps were measured from the half of the cell (0.2 m long path).

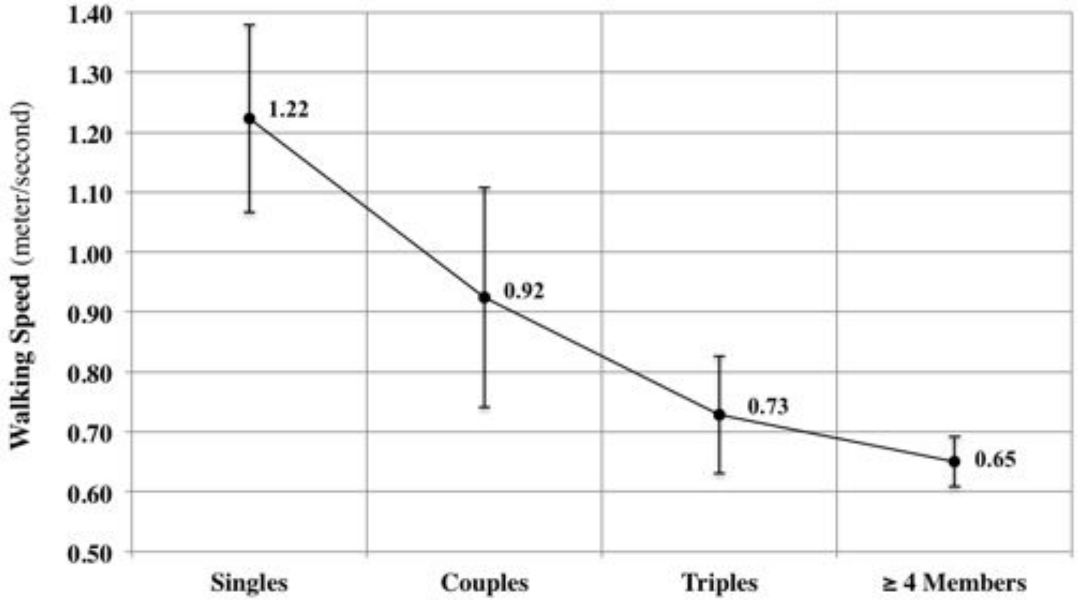

Figure 5.11: *The average walking speed (meter/second) of single pedestrians, couples, triples and groups of four members (with standard deviation).*

of four members, couples and triples and triples and groups of four members (p value<0.05). In conclusion, results showed that the average walking speed of group members (including couples, triples and groups of four members) was 37% lower than the speed of single pedestrians.

The correlated results about the walking path and speed of the sampled pedestrians showed that in situation of irregular flow single pedestrians crossed the space with frequent changes of directions in order to maintain their velocity, avoiding perceived obstacles like slower pedestrians or groups. On the contrary, groups adjusted their spatial arrangement and speed to face the contextual condition of irregular flow, with overtaking and waiting dynamics among members in order to regroup in case of an oncoming pedestrian or group. This is related to the difficulty in coordinating an overall change of direction among group members and the tendency to preserve the possibility to communicate by maintaining spatial cohesion among members. In conclusion, considering the equal length of the paths of couples, triples and group of four members, results showed a significant group size effect on walking speed.

Group Proxemics Dispersion

This Section presents the results achieved by means of the analysis of the spatial dispersion among group members while walking in condition of irregular flows (LOS B). The dispersion of walking groups (i.e. the degree of spatial distribution among

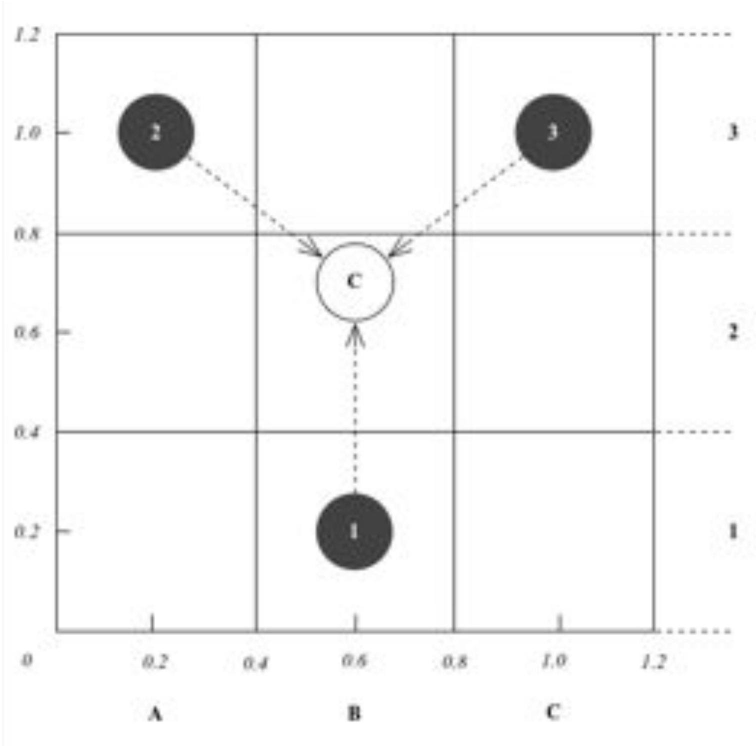

Figure 5.12: *The positions of each group member (1, 2, 3), considering the alphanumeric grid (1: B1; 2: A3; 3: C3) and the Cartesian plane (1: 0.6-0.2; 2: 0.2-1.0; 3: 1.0-1.0), and the estimate position of the centroid of the group (C).*

group members) has been estimated as the mean of the distances between each member and the geometrical centre of the group (i.e. *centroid*). In order to detect the reciprocal spatial positions of group members, the trajectories of the sampled pedestrians (15 couples, 10 triple and 8 groups of four members) were further analyzed, considering the positions of each group member within the alphanumeric grid frame by frame. In particular, the video images related to each group were analyzed every 40 frames[3], starting from the co-presence of the all members in the monitored area of the walkway delimited by the grid.

In order to perform data analysis each pedestrian was considered as a point without mass in a two-dimensional plane and the centre of the cell occupied by the feet of each pedestrian as its own actual position. By using a specific designed algorithm for automated computing, it was possible to perform a geometrical transformation of the positions of each pedestrian in a Cartesian-continuous plane, to estimate the position of the centroid of each group (obtained as the arithmetic mean of all spatial positions of

[3]According to the quality and definition of the video images, the time interval between two frames corresponded to about 1.79 seconds; by means of this sampling it was possible to consider the position of each group member taking into account ten snapshots for each group.

the group members) and to measure the average distance between each group member and the centroid, in order to estimate the group spatial dispersion (see Fig. 5.12).

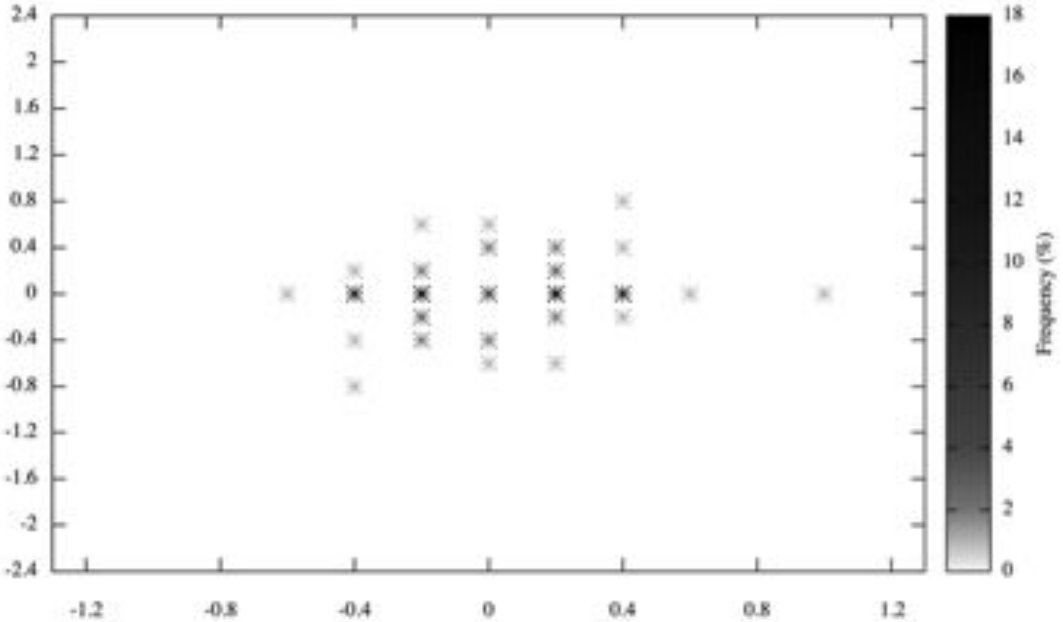

Figure 5.13: *The aggregated positions of couples, normalized with respect to the centroid and the movement direction (from South to North). The X-axis and Y-axis report the distances from the centroid and the points, and depict relative frequency of the occupation of a given position with a darker shade of grey for higher frequencies.*

Two tailed t-test analyses were used to identify differences in spatial dispersion among couples (0.35 m, sd 0.14), triples (0.53 m, sd 0.17) and groups of four members (0.67 m, sd 0.12). Results showed a significant difference in spatial dispersion between couples and triples (p value$<$0.05), couples and groups of four members (p value$<$0.01). No significant differences (p value$>$0.05) between triples and groups of four members. In conclusion, results showed that couples walked 41% less disperse than triples and groups of four members.

In order to detect regularities in spatial positioning and alignment among group members while walking, the positions of each group members were normalized with respect to the centroid of the group and the movement direction (the positions of the group members with a direction of movement from North to South were rotated of 180° angle degrees). Results showed that couples walked side by side with a line abreast pattern (68% of couples and 30% of triples), while groups of four members walked much more dispersed, due to the continuous arrangements in spatial positioning (as illustrated in Fig. 5.13, Fig. 5.14 and Fig. 5.15).

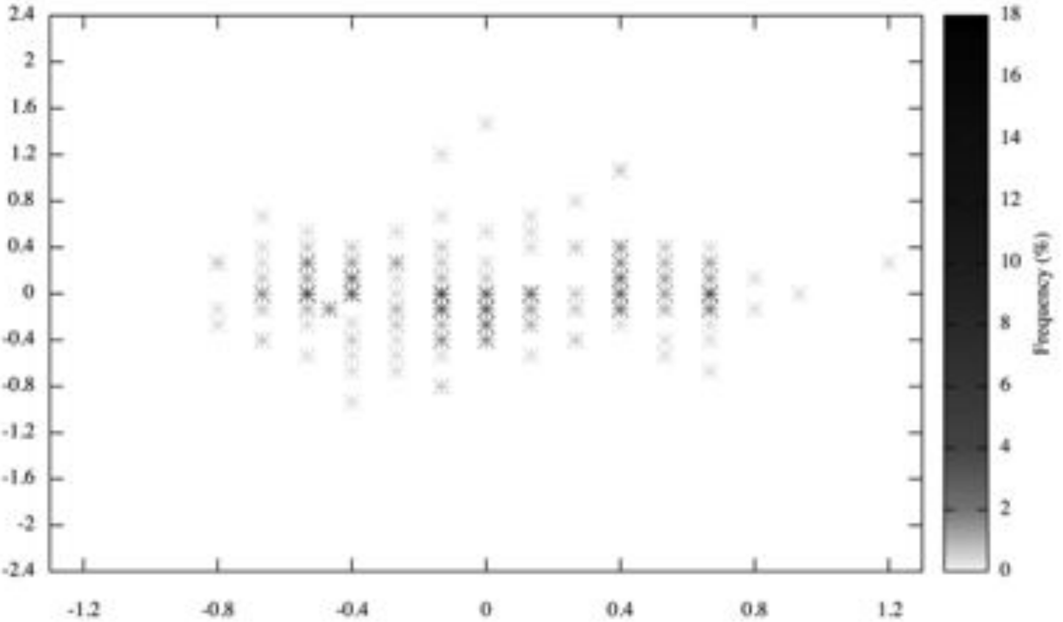

Figure 5.14: *The aggregated positions of triples, normalized with respect to the centroid and the movement direction (from South to North). The X-axis and Y-axis report the distances from the centroid and the points, and depict relative frequency of the occupation of a given position with a darker shade of grey for higher frequencies.*

5.4 Final Remarks

The Chapter presented the results achieved by means of the unobtrusive observation of pedestrian circulation dynamics in urban crowded scenarios. The proposed empirical studies were focused on the impact of proxemics, grouping and density on the overall phenomenon. The Chapter comprised a detailed description of both data collection and analysis phases, with reference to the observation of: the pedestrian flows oncoming to the Campus of the University of Milano-Bicocca (Italy) in order to participate to the admission test of the Faculty of Psychology (September 1st, 2011), and the pedestrian circulation dynamics at the Vittorio Emanuele II gallery, a commercial-touristic walkway situated in the Milan city center (Italy) (November 24th, 2012).

Results are respectively presented in Section 5.2.2 and Section 5.3.2, with reference to level of density and service, pedestrian flows composition in terms of groups, group spatial arrangement and dispersion during locomotion, trajectories and walking speed of both singles pedestrians and group members. Considering the observation carried out at the Campus of the University of Milano-Bicocca, No. 1897 were manually counted. Results showed that: the average level of service corresponded irregular flows in condition of low-medium density (LOS B), the majority of the observed pedestrians were group members (66%), with a dominant presence of couples in the streaming of

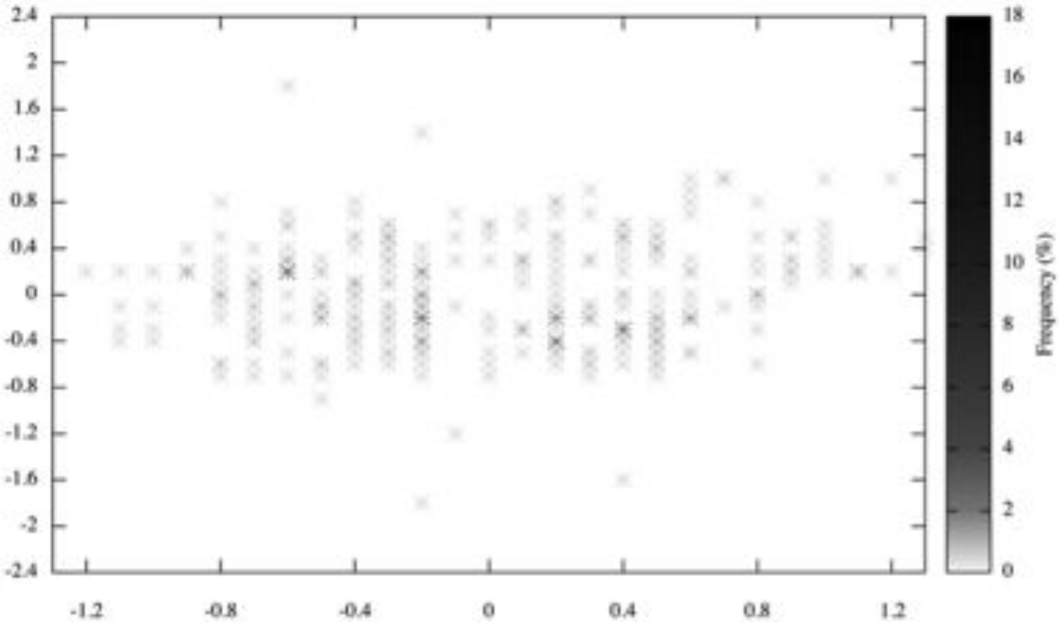

Figure 5.15: *The aggregated positions of groups of four members, normalized with respect to the centroid and the movement direction (from South to North). The X-axis and Y-axis report the distances from the centroid and the points, and depict relative frequency of the occupation of a given position with a darker shade of grey for higher frequencies.*

passersby. Couples and triples walked with a lane formation pattern (respectively 97% and 66% of them), while groups composed of four members walked with a rhombus-like pattern. The average walking speed of group members was 9% lower than the one of single pedestrians.

Considering the observation carried out at the Vittorio Emanuele II gallery, No. 7773 people were manually counted. Results showed that: the average level of service corresponded irregular flows in condition of low-medium density (LOS B), the 84% of the observed pedestrians were group members. Couples walked with a lane formation pattern (94%), triples with a V-like pattern (58%), while groups of four members split in two dyads (32%) or walked with a lane formation pattern (29%). The walking path of singles was 4% longer than the average path of group members. Group members walked 37% slower than singles. Couples walked 41% less disperse than triples and groups of four members.

The presented results showed that it is crucial to consider the impact of grouping on pedestrian circulation dynamics, considering the massive presence of groups within the observed pedestrian flows. Considering the observed level of density (LOS B), results showed that single pedestrians walked faster than groups, modulating their path in order to maintain their velocity. Moreover, the number of group members has a negative impact on both walking path, speed and spatial dispersion, due to the higher probability of groups to disperse in case of oncoming pedestrians and the needed time to adjust their spatial arrangement to regroup.

In conclusion, the achieved results represent an useful contribution for the understanding of pedestrian crowd dynamics, once again in situations characterized by low-medium density[4]. Further empirical investigations would be necessary to actually compare results in situation of high density, considering also the opportunity to employ more sophisticated and at least partly automated technologies for data analysis. According to the proposed methodological approach, the achieved results represent an extremely interesting and significant body of empirical evidences finally aimed at supporting the validation of the pedestrian crowd simulation platform MAKKSim.

Pedestrian Circulation Dynamics in Urban Crowded Scenarios	
The Admission Test of the University of Milano-Bicocca	
Crowd Estimation	LOS B (irregular flow in situation of low-medium density)
Crowd Composition	1897 people, 44% single pedestrians, 66% groups: 77% couples, 19% triples and 4% larger groups
Group Proxemics	97% of couples and 66% of triples line abreast pattern, 30% four members groups rhombus-like pattern
Walking Speed	groups walk 9% slower than single pedestrians
The Vittorio Emanuele II Gallery	
Crowd Estimation	LOS B (irregular flow in situation of low-medium density)
Crowd Composition	No. 7773 people, 16% single pedestrians, 84% groups: 52% couples, 20% triples and 28% larger groups
Group Proxemics	94% of couples line abreast pattern, 59% of triples V-like pattern, 33% four members groups two dyads pattern
Walking Path	singles walking path is 4% longer than groups
Walking Speed	groups walk 37% slower than single pedestrians
Group Dispersion	group dispersion of triples and four members groups is 41% higher than couples

Table 5.2: *A synthesis of the results achieved by means of the observation of pedestrian circulation dynamics in urban crowded scenarios, with reference to the impact of density, grouping and proxemics on the overall phenomenon (e.g., LOS, crowd composition, group proxemic arrangement and dispersion, walking path and speed).*

[4]According to the objectives of this work, the observed low-medium level of density allowed to easily detect groups within the observed pedestrian flows and to analyze their proxemic behavior while walking.

Acknowledgement

The presented studies were partially funded by CROWDYXITY s.r.l, a spin-off of the University of Milano-Bicocca. The surveys were respectively carried out thanks to the authorization of the Authorities of the University of Milano-Bicocca and the Milano's Municipality. The existing Italian legislation about privacy (d.lgs. 196/2003) was consulted and complied in order to exceed ethical issues about the privacy and anonymity of the people recorded within the pedestrian flows without their consent. The achieved results are respectively published in Federici et al. (2012) and Bandini et al. (2013).

6 In Vitro Experiment of Human Locomotion-Spatial Behavior

This Chapter presents the results achieved by means of the experimental investigation of human locomotion and spatial behavior in laboratory setting (considering both individual and group level of investigation). The first study was focused on the combined impact of turning path and grouping on pedestrian dynamics in high density situations (see Section 6.2). The second experiment was focused on the impact of walking speed on the size of personal space, considering both static and motion situations (see Section 6.3). According to the proposed methodological approach, the presented experimental investigations were aimed at defining descriptive set of metrics and parameters for characterizing pedestrian crowd dynamics and supporting the validation of in silico simulations.

6.1 Introduction

This Chapter presents several empirical studies aimed at experimentally investigating human locomotion and spatial behavior (considering both individual and group levels of investigation). According to the proposed methodological approach, data collection and analysis were carried out considering several indicators related to proxemic behavior during locomotion in situation of variable density (e.g., spatial arrangement of walking groups, personal space). In particular, the Chapter includes the results achieved by means of two empirical studies focused on (*i*) the combined impact of turning path and grouping on pedestrian dynamics in situation of high density and (*ii*) the impact of walking speed on the size of pedestrian personal space.

The first experimental contribution was aimed at studying pedestrian crowd dynamics, considering the combined impact of the environment physical features and social interactions among pedestrian on normal and orderly egress flows. Recent studies pointed out the negative impact of circuitous and turning paths on pedestrian crowd dynamics[1] (Courtine and Schieppati, 2003; Steffen and Seyfried, 2009; Shiwakoti et al.,

[1] As highlighted in Chertkoff and Kushigian (1999), the survivors from the Beverly Hills Supper Club fire on 28th May 1977 in Kentucky-U.S. (where 165 people died and 70 others were seriously injured)

2011; Dias et al., 2012). The experiment was aimed at investigating the effect of different angle paths, characterized by 0°, 45°, 60° and 90° degrees turning angles, on pedestrian flow rate. Moreover, previous studies have highlighted the importance to consider pedestrian crowd dynamics as influenced by the presence of groups (Daamen and Hoogendoorn, 2003; Köster et al., 2011; Peacock et al., 2011), which generate patterns of movement generally respected by other pedestrians (both in normal and emergency situations) (Sime, 1995; Mawson, 2007). For this reason, the proposed experiment was aimed at investigating the impact of grouping on the overall phenomenon, taking into account groups walking speed and spatial arrangement.

The second experimental contribution was aimed at collecting empirical evidences about human proxemic behavior, with particular reference to the size of personal space during locomotion (Sommer, 1969) (i.e. the area immediately surrounding individuals, into which strangers cannot intrude without arousing discomfort). In particular, pedestrian personal space was assumed to be larger from the one in static situations due to the need to avoid physical contact and collision with oncoming obstacles and pedestrians. This anticipation effect was supposed to have an impact on pedestrian crowd dynamics, as characterized by competitive interactions and sudden detouring maneuvers, due to the low degree of freedom for spatial positioning.

Although innovative results have been recently achieved regarding the neural substrates of personal space as mediated by amygdala activation functions (Kennedy et al., 2009), only few contributions empirically investigated its spatial configuration during locomotion[2] (Wolff, 1973; Pettré et al., 2009; Suma et al., 2012; Gérin-Lajoie et al., 2005). According to the pioneering work of John J. Fruin (1971), pedestrian personal space is defined as composed of: a pacing zone, required for foot placement, and a sensory zone based on locomotor vision (Gibson, 1950), that is necessary to evaluate and react in time to environmental stimuli. Taking advantage from this framework, the proposed experimental investigation was aimed at testing the impact of walking sped on the size of front zone of pedestrian personal space (as presented in Chapter 3 and illustrated in Figure 3.1).

The performed experimental investigations are presented in Section 6.2 and Section 6.3, with particular reference to the objectives, hypotheses and methodologies of each studies (e.g., experimental samples, settings, design and procedures). The achieved results about human locomotion and spatial behavior (e.g., flow rate, group proxemic

described the presence of circuitous paths as one of the main factors that caused the disaster.

[2]For instance, the results gathered by means of a quasi experiment carried out by Wolff (1973) showed that in high density situations pedestrians tend to avoid collision from a distance of 1.5 meter, while in low density cases this would rise to much greater distances. More recently, Pettré et al. (2009) and Suma et al. (2012) have respectively proposed experimental investigations of physical and perceptual factors related to pedestrian locomotion and collision avoidance dynamics in case of static and dynamic obstacles. Finally, although the contribution carried out by Gérin-Lajoie et al. (2005) is explicitly focused on the experimental measurement of the elliptical shape of personal space while moving, it presented a scarce level of external validity due to the procedure was based on the interaction between a human walker and a moving manikin mounted on an overhanging rail.

spatial arrangement, walking speed of both singles pedestrians and group members, the size of the front zone of personal space in both static and motion situations) are respectively presented in Section 6.2.2 and Section 6.3.2. The chapter ends with final remarks about the collected empirical evidences and their employment towards the definition of descriptive set of metrics and parameters for characterizing human locomotion-spatial behavior and support the validation of pedestrian crowd modeling and simulations.

6.2 Pedestrian Dynamics, Turning Path and Grouping

The proposed empirical study was aimed at investigating the impact of turning paths and grouping on pedestrian dynamics in high-density situation. First, the impact of the physical features of different angle paths (0°, 45°, 60° and 90° degrees) on flow rate was considered through Hypothesis 1. Then, the walking speed of both single pedestrians and group members were examined through Hypothesis 2. The impact of different angle paths (0°, 45°, 60° and 90° degrees) on the walking speed of both single pedestrians and group members was examined in Hypothesis 3. Thanks to the collaboration with the Institute of Transport Studies, the experiment was performed on April 19th 2012, at the Clayton Campus of the Monash University (Melbourne, VIC, Australia).

- **Hp1**: Flow rate is negatively affected by the increase in turning angle;
- **Hp2**: In high-density situations, the walking speed of group members is lower than single pedestrians;
- **Hp3**: In high-density situation, the walking speed of both singles and group members is negatively affected by the increase in turning angle.

6.2.1 Method

Sample

No. 68 subjects (45 males and 23 females, aged from 20 to 30 years old) were recruited from the list of the students of the Monash University (Melbourne, VIC, Australia) and participated the experimental study. In order to test the second and third hypotheses we considered the walking speed of a portion of the participants. This included 30 subjects composed of 15 singles and 15 group members (divided in four couples, one triple and one group of four members; mixed gender). The participants spontaneously organized themselves into groups during the experimental procedure, since some of them were classmate and friends. Differences in gender, age, culture, group size and spatial arrangement were not considered in this study.

Setting

The experimental setting was set up with a walking path delimited by desks and markers drawn on the floor by using scotch tape (as illustrated in Fig. 6.1). The angle paths (0°, 45°, 60° and 90° degrees) were arranged during the experiment asking the participants to wait in the gathering area. In order to control the impact of participants' tiredness on results, the experiment was performed starting from the 45° degrees to 60°, 90° and 0° degrees angle paths. The experimental procedure was repeated three times for each scenario in order to compare and evaluate the significance of results. Three video cameras with tripods were employed for video footages and data analysis.

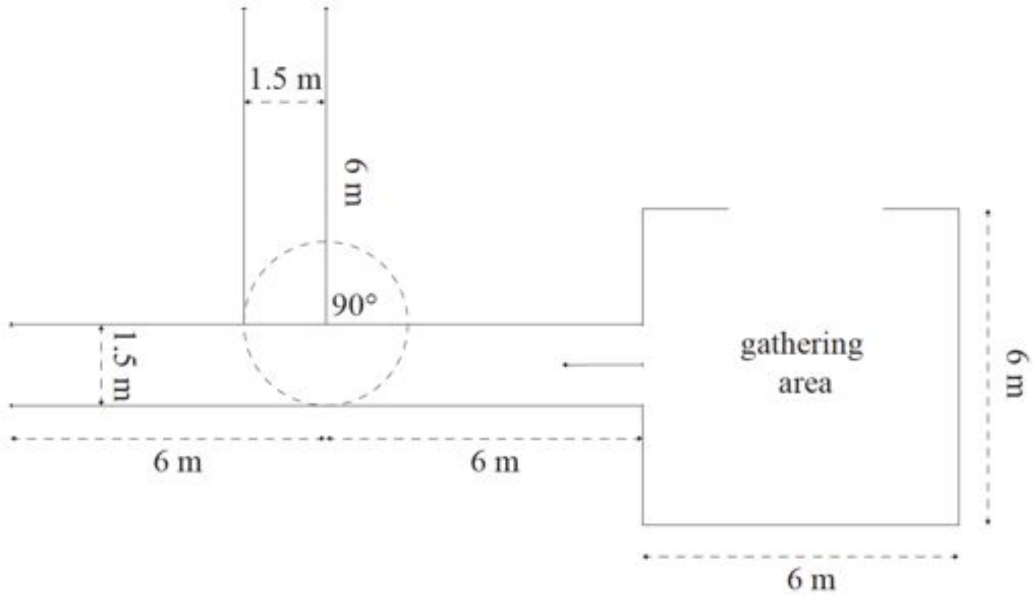

Figure 6.1: *A schematic representation of the experimental setting (not to scale), composed of a gathering area, a corridor path with starting and ending points, an angle path in the middle of the corridor (as illustrated, the paths with 0° and 90° degrees) and a turning path to come back to the gathering area.*

Experimental Design

In order to test the first hypothesis, the experimental procedure was designed considering the *degree of angle path* (0°, 45°, 60° and 90° degrees) as the independent variable and the level of flow rate within the path (pedestrian/minute/meter) as the dependent variable. In order to test the second and third hypotheses, the experimental procedure was designed between subjects in relation to the independent variables *state of the subject* (subject alone or group member) and *degree of angle path*; the walking speed of single and group members was considered as dependent variable (the walking speed of group members was measured considering the last member of each group reaching the endpoint of the path). The identification of groups in the streaming of passers-by was assessed considering verbal and non-verbal communication among participants (e.g., talking, gesticulation, visual contact, body orientation and spatial arrangement).

Experimental Procedure

The participants were taken into the experimental room for 120 minutes and were asked to walk freely through the path at normal speed for three runs for each scenario (see Fig. 6.2). As illustrated in Figure 6.1, the walking path was composed of a gathering area (6 meters by 6 meters), a corridor with starting and ending points (1.5 meters width and 12 meters length), an angle path in the middle of the corridor (0°, 45°, 60° and 90° degrees) and a turning path to come back to the gathering area.

Figure 6.2: *As illustrated from the left to the right side, the snapshots extracted from the video recorded images during the experimental procedures with 0° and 90° degrees angle paths (walking groups are highlighted in colors).*

6.2.2 Results

A first analysis was devoted on estimating the level of flow rate in relation to the tested angle paths (0°, 45°, 60° and 90° degrees). Then, the collected data were compared by means of two tailed t-test analyses, in order to check the impact of the independent variable *degree of angle path* on pedestrian flow rate. Finally, two tailed t-test analyses among procedures were devoted to check the impact of the independent variables *degree of angle path* and *state of the subject* (subject alone or group member) on speed.

Flow Rate

According to the Highway Capacity Manual (Milazzo II et al., 1999) and the level of service criteria (Fruin, 1971), the level of density within the path was estimating by counting the number of people walking through a certain unit of space (meter) in a certain unit of time (minute). Data analysis was devoted on estimating the level of flow rate in relation to the tested angle paths (0°, 45°, 60° and 90° degrees) (see Table 6.1).

Results showed that the average flow rate (65.61 pedestrian/minute/meter, sd 3.48) corresponded to LOS E (irregular flow in condition of high density). In order to test the first hypothesis, the collected results were compared by means of two tailed t-test analyses. Results showed a significant difference in flow rate between the angle paths with 45°-60° degrees (p value<0.05) and the angle paths with 0°-60°, 0°-90° and 45°-90° degrees (p value<0.01). No significant differences (p value>0.05) between the angle paths with 0°-45° and 60°-90° degrees. In conclusion, results (see Figure 6.3) demonstrated that the physical features of the angle path with 60° degrees have a significant negative impact on pedestrian flow rate (12% less effective compared to the angle path with 45° degrees). For this reason the first hypothesis can be partially accepted.

Angle Paths	Flow Rate	Level of Service
0° degrees	74.18 pedestrian/minute/meter (sd 2.12)	LOS E
45° degrees	70.17 pedestrian/minute/meter (sd 3.71)	LOS E
60° degrees	61.30 pedestrian/minute/meter (sd 5.15)	LOS E
90° degrees	56.81 pedestrian/minute/meter (sd 2.95)	LOS E

Table 6.1: *The average flow rate (with standard deviation) and level of service related to the tested angle paths (0°, 45°, 60° and 90° degrees).*

Walking speed

Two tailed t-test analyses were used to check the differences among the walking speed of single pedestrians and group members within each angle path (0°, 45°, 60° and 90° degrees) (as illustrated in Table 6.2). Results showed that group members walked slower than singles and that this differences was statistically significant considering each tested scenario (p value<0.01). In summary, results showed that in situation of high density the average walking speed of group members among all scenarios was 9% lower than the one of single pedestrians. Overtaking and waiting dynamics among group members were observed in correspondence of the turning path. The proxemic behavior of walking groups was characterized by the splitting of spatial arrangements to avoid group dispersion and spatial collision with other pedestrians while walking. Therefore, the second hypothesis is valid.

In order to test the third hypothesis, the average walking speed of both singles and group members were compared among all scenarios by using two tailed t-test analyses (see Figure 6.3). Results showed a significant difference (p value<0.01) in walking speed of both singles and group members between the 0°-60°, 0°-90°, 45°-60° and 45°-90° degrees angle paths. No significant differences (p value>0.05) were identified between the scenarios with 0°-45° and 60°-90° degrees. In summary, results showed that the physical features of the angle paths with 60° degrees have a negative impact on the walking speed of both singles and group members. This is 7% lower compared to singles walking on 45° degrees path, and 11% lower compared to the group members walking on the 45° degrees path. For this reason the third hypothesis is partially confirmed.

Angle Path	Speed of Singles	Speed of Groups	t-test
0° degrees	1.00 meter/sec (sd 0.07)	0.89 meter/sec (sd 0.01)	p value<0.01
45° degrees	0.95 meter/sec (sd 0.08)	0.88 meter/sec (sd 0.04)	p value<0.01
60° degrees	0.87 meter/sec (sd 0.08)	0.78 meter/sec (sd 0.04)	p value<0.01
90° degrees	0.81 meter/sec (sd 0.05)	0.76 meter/sec (sd 0.03)	p value<0.01

Table 6.2: *The average walking speed (with standard deviation) of single pedestrians and group members, and the results achieved by means of two tailed t-test analyses among angle paths (0°, 45°, 60° and 90° degrees).*

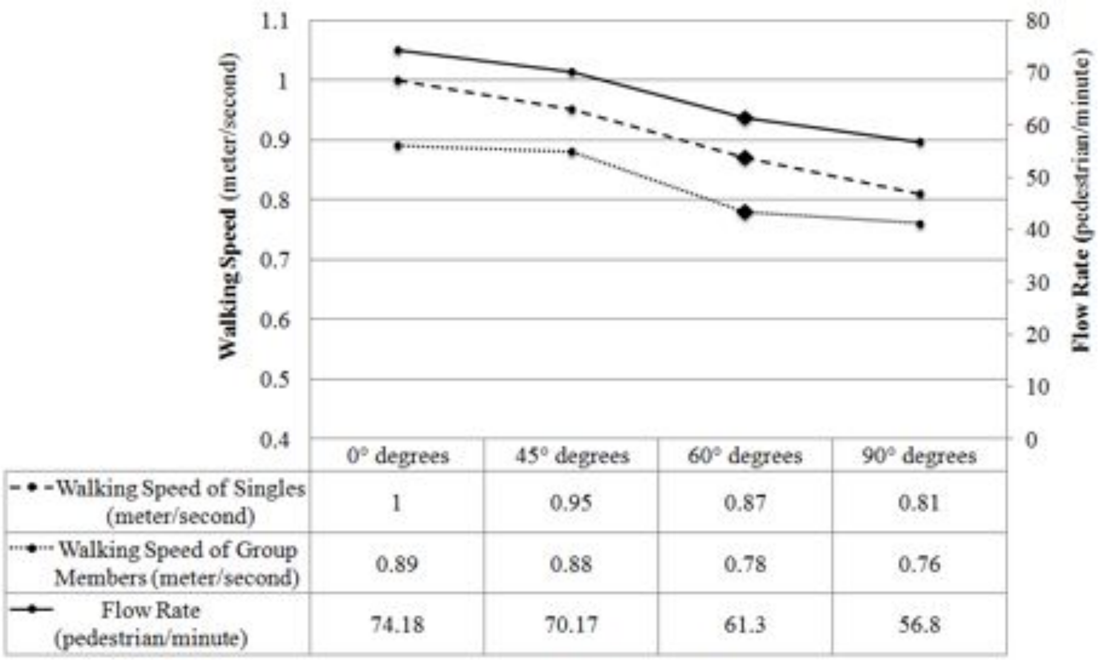

Figure 6.3: *The average flow rate and walking speed of single pedestrians and group members, considering each tested scenario (0°, 45°, 60° and 90° degrees angle paths).*

6.3 Pedestrian Personal Space

The proposed experimental study was aimed at measuring the size of the front zone of personal space in static and motion situations, taking into account the impact of walking speed. In particular, the front zone of pedestrian personal space was assumed to be larger than the one in static situations and linearly speed-dependent. This is due to the need of an additional margin projected towards the direction of movement to anticipate and avoid in time the spatial intrusion of oncoming pedestrians. Thanks to the collaboration with the RCAST research center, the experiment was performed on June 8th 2013, at the Nishinari's Lab of The Tokyo University (Tokyo, Japan).

- **Hp**: Depending on walking speed, the front zone of personal space in motion situations is larger than the one in static situations

6.3.1 Method

Sample

20 male subjects with sufficient visual capacity (if necessary fitted with glasses or contact lenses), aged from 18 to 25 old, were recruited from the list of The Tokyo University students. The sample was composed of 17 Japanese, 2 Vietnamese and 1 Chinese. Differences in age and culture have not been considered in this study.

Setting

The laboratory setting (8 meters long and 7 meters large) was divided in three rooms by using wall fences (5 meters long and 2 meters high, see Fig.6.4 and Fig.6.5). This was aimed at reducing the duration time of the overall experiment (performing three experimental procedures in parallel), limiting the impact of subjects' tiredness on results. Moreover, the use of wall fences permitted to isolate participants within the rooms, in order to control the impact of imitative behavior on results (i.e. *Hawthorne effect*). During testing only four experimenters (involved in data collection and participants management) and six experimental subjects were in the laboratory at any given time. The setting was equipped with unobtrusive video-recording equipment. A comfortable degree of lightness and temperature was maintained into the room during the experimental session.

Experimental Design

The subject's *state of movement* (stationary/walking straight ahead) and *walking speed* (low/medium/high speed) were defined as independent variables. The size of the front zone of personal space was deduced from the effect of discomfort caused by spatial invasion. Considering the modalities of the independent variables (2x3) the experimental procedure was designed within subjects.

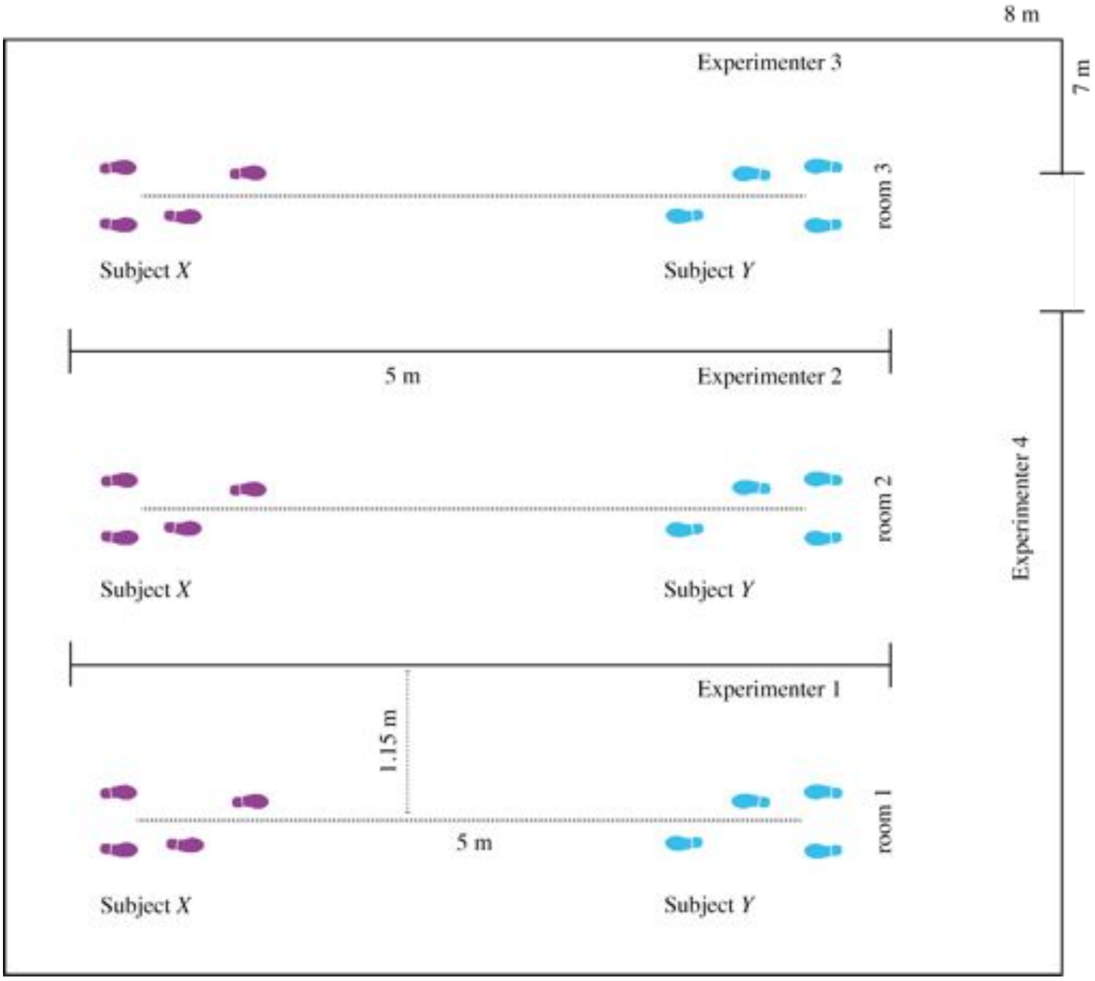

Figure 6.4: *A schematic representation of the setting (not in scale), divided in three different experimental rooms by using wall fences. The rooms were set up with trajectories and foot markers drawn on the floor in order to manage the subjects'walking speed.*

Experimental Procedures

The size of the front zone of personal space in static and motion situations was measured by means of a revised version of the *stop-distance* procedure[3] (Hayduk, 1983), the most frequently used paradigm to empirically study the tolerance for interpersonal proximity in static situations. Considering the modalities of the independent variable *state of movement* of the subject, the experiment was composed of three different procedures:

[3]The stop-distance procedure (Hayduk, 1983) consists of asking the participant to stop the approach of the experimenter (who approaches the subject from different directions, walking slowly and with short steps) when he feels uncomfortable about spatial nearness. The distance between them is used to define the size of the subject's personal space.

(*A*) stop-distance procedure, focused personal space in static situations; (*B*) approach-distance procedure, focused on pedestrian personal space while walking towards a stationary person; (*C*) locomotion-distance procedure, focused on pedestrian personal space while moving towards an oncoming pedestrian (see Table. 6.4).

	Static Situation	**Motion Situations**	
	Experiment A	**Experiment B**	**Experiment C**
Subject *X*	*Stationary*	*Approaching*	*Approaching*
Subject *Y*	*Approaching*	*Stationary*	*Approaching*
Procedure	Stop-Distance	Approach-Distance	Locomotion-Distance

Table 6.3: *A schema of the designed experimental procedures (stop-distance* A*, approach-distance* B*, locomotion-distance* C*), aimed at measuring the size of the front zone of personal space in static and motion situations (considering the state of movement of the subjects).*

In order to test the impact of the independent variable *walking speed* on personal space, each procedure was repeated three times according to the modalities of the variable (e.g., A1-low speed, A2-medium speed, A3-high speed). In order to control and maintain constant the speed during the approach, participants were asked to walk following trajectories and foot markers drawn on the floor (positioned at a distance of 20 cm, from the heel of the front foot to the toe of the foot positioned behind) (see Fig. 6.4) and to synchronize their gait to metronome background sounds. Considering the length of steps, the standard speed used for design purposes of traffic lights in crossing points (1.22 meter/sec) (Knoblauch et al., 1996) was used to test the impact of medium speed on personal space. According with that, metronome background sounds were configured with three different sets of pace (low speed: 70 bpm-0.93 m/sec; medium speed: 90 bpm-1.23 m/sec; high speed: 110 bpm-1.46 m/sec).

The duration time of the whole experiment was about 2 hours. In order to control learning and tiredness effects on results, participants were randomly coupled (subject *X* and subject *Y*) and assigned to the experimental procedures making them wait few minutes between one and the other. The experimental procedures were performed with a random order. Procedures were preliminarily illustrated to participant during a short briefing.

- **Stop-Distance Procedure *A*:** Subject *Y* approaches subject *X* walking straight ahead from a distance of 5 meters (neutral facial expression, not speaking, eliminating eye contact by constantly gazing at the subject's *X* neckline). Subject *X* remains stationary with head and eyes straight ahead, and stops the approaching when he feels uncomfortable about the closeness of subject *Y* by raising his right arm on the side. The distance between participants is measured as the size of the front zone of personal space of subject *X* in static situations;

- **Approach-Distance Procedure *B*:** Subject *X* approaches subject *Y* walking straight ahead from a distance of 5 meters (with head and eyes straight ahead). Subject *Y* remains stationary (with head and eyes straight ahead, neutral facial expression, not speaking, eliminating eye contact by constantly gazing at the subject's *X* neckline). Subject *X* is asked to stop the approaching when he feels uncomfortable about the closeness of subject *Y*. The distance between participants is measured as the size of the front zone of subject *X* pedestrian personal space, walking towards a stationary person;

- **Locomotion-Distance Procedure *C*:** Subject *X* and subject *Y* approach the each other walking straight ahead from a distance of 5 meters (with neutral facial expression, not speaking, eliminating eye contact by constantly gazing at the subject's neckline). Subject *X* is asked to stop the approaching when he feels uncomfortable about the closeness of subject *Y*; subject *Y* is asked to immediately stop after. The distance between participants[4] is measured as the size of the front zone of subject (*X*) pedestrian personal space, walking towards on coming pedestrian.

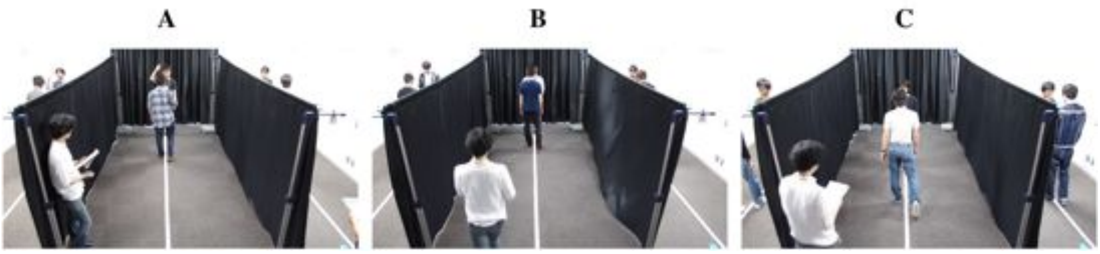

Figure 6.5: *As illustrated from the left to the right side, the snapshots extracted from the video recorded images during the experimental procedures stop-distance* A, *approach-distance* B *and locomotion-distance* C *(respectively aimed at investigating the size of the front zone of personal space in static and motion situations).*

6.3.2 Results

The average size of the front zone of personal space was measured considering each experimental procedure. The collected data were compared by means of oneway analysis of variance (ANOVA) and two tailed t-tests. This was aimed at testing the impact of the independent variable *walking speed* and its modalities on the size of personal space.

[4]Regarding procedures *A1*, *B1*, *B2* and *B3*, the distance between participants was measured from the point in the middle of the feet of subject *X* to the toe of front foot of subject *Y*. Regarding procedures *A2*, *A3*, *C1*, *C2* and *C3*, walking speed and procedure itself were found to have a delay effect on stopping maneuver. For this reason in those cases the distance between participants was measured from the point in the middle of the feet of subject *X* to the toe of rear foot of subject *Y*.

Subsequently, two tailed t-test analyses among procedures were devoted to test the impact of the independent variable *state of movement* of the subject and its modalities on personal space. The results achieved by means of the stop-distance procedure *A1* (low speed related) were used as a benchmark value, in order to test the difference between the size of the front zone of personal space in static and motion situations (as illustrated in Fig. 6.6).

Stop-Distance Procedure

Results showed a significant walking speed effect on personal space in static situations (ANOVA, p value<0.05) (this is referred to the walking speed of subject *Y* approaching the stationary subject *X*). The average size of the front zone of personal space in static situations when approached at low speed (procedure *A1*) was 72.15 cm (sd 25.71 cm). Regarding procedures *A2* and *A3*, the average size of personal space when approached at medium and high speed were respectively 94.4 cm (sd 22.12 cm) and 96 cm (sd 29.16 cm). Two tailed t-test analyses showed a significant difference (p value<0.05) between procedures *A1*-*A2* and procedures *A1*-*A3*. No significant difference (p value>0.05) between procedures *A2*-*A3*. In conclusion, results showed that the size of the front zone of personal space in static situations is affected by the difference in walking speed of the approaching subject. Being approached by a stranger at medium and high speed could elicit in the subject a fright reaction, with the consequent need to avoid spatial intrusion from a larger distance.

Approach-Distance Procedure

Results showed that walking speed had not a significant impact on pedestrian personal space while moving towards a stationary person (ANOVA, p value>0.05) (this is referred to the walking speed of subject *X* approaching the stationary subject *Y*). The average size of the front zone of pedestrian personal space when approaching a stationary obstacle at low speed (procedure *B1*) was 70.1 cm (sd 22.96 cm). Regarding procedures *B2* and *B3*, the average size of pedestrian personal space at medium and high speed were respectively 71.7 cm (sd 20.29 cm) and 68.45 cm (sd 23.09 cm).

The obtained results were compared with the size of the front zone personal space in static situations (stop-distance procedure *A1*, low speed related): this showed no significant difference among results (t-test, p value>0.05). In conclusion, results showed that the size of the front zone of pedestrian personal space when moving towards a stationary person is not affected by the difference in walking speed and that it is similar to the size of personal space in static situations. This could be related to the subject's capability to estimate in time the required space to avoid spatial intrusion, in spite of the differences in walking speed.

Locomotion-Distance Procedure

Results showed a significant walking speed effect on pedestrian personal space while moving towards an oncoming pedestrian (ANOVA, p value<0.05) (this is referred to the walking speed of subject *X* and subject *Y* approaching the each other). Regarding procedures *C1* and *C2*, the average size of pedestrian personal space in case of a reciprocal approach at low and medium speed were respectively 71.45 cm (sd 21.78 cm) and 68.9 cm (sd 24.02 cm). The average size of pedestrian personal space during reciprocal approach at high speed (procedure *C3*) was 91.1 cm (sd 30.3 cm). Data were compared by means of t-test analyses. Results showed a significant difference (p value<0.05) between procedures *C1-C3* and procedures *C2-C3*. No significant difference (p value>0.05) between procedures *C1-C2*. In conclusion, results showed that the size of the front zone of pedestrian personal space while moving towards an oncoming pedestrian at high speed is larger than the ones at low and medium speed.

Further t-test analyses showed that pedestrian personal space at high speed is significantly different (p value<0.05) respect to the size of the front zone of personal space in static situations (stop-distance procedure *A1*, low speed related). This partially confirmed the hypothesis, showing that in case of a reciprocal approach at high speed (1.46 meter/sec) the front zone of pedestrian personal space is larger than the one in static situations, due to the need of an additional margin projected ahead towards the direction of movement in order to anticipate the spatial intrusion of oncoming pedestrians.

	Static Situation	Motion Situations	
	Experiment A	**Experiment B**	**Experiment C**
Low Speed	72.15 cm (sd 25.71)	70.10 cm (sd 22.96)	71.45 cm (sd 21.78)
Medium Speed	94.40 cm (sd 22.12)	71.70 cm (sd 20.29)	68.90 cm (sd 24.02)
High Speed	96.00 cm (sd 29.16)	68.45 cm (sd 23.09)	91.10 cm (sd 30.30)

Table 6.4: *The results achieved by means of the experimental procedures stop-distance A, approach-distance B and locomotion-distance C, aimed at measuring the size of the front zone of personal space in static and motion situations considering the impact of walking speed (e.g., low speed: 0.96 m/sec, medium speed: 1.23 m/sec, high speed: 1.46 m/sec).*

6.4 Final Remarks

The Chapter presented several empirical studies aimed at experimentally investigating human locomotion and spatial behavior in laboratory setting. The proposed empirical studies were focused on testing the combined impact of turning path and grouping on pedestrian dynamics in situation of high density and measuring the size of the front zone of personal space during locomotion.

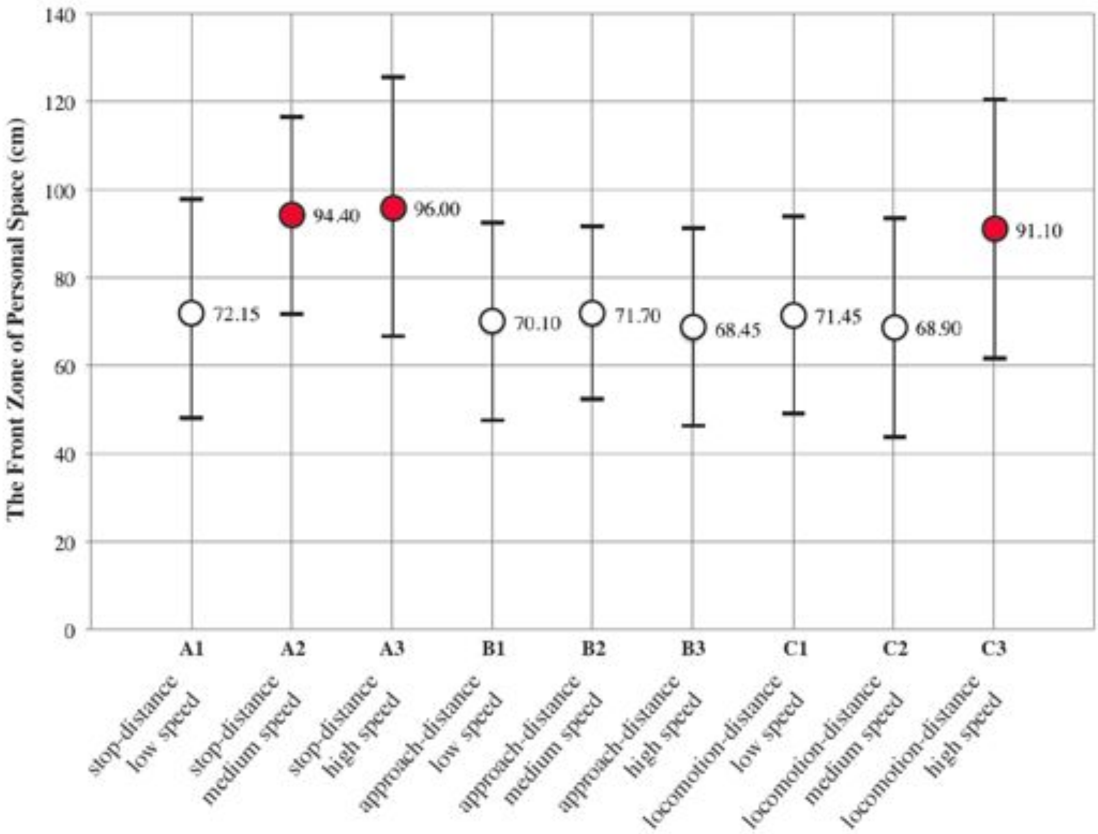

Figure 6.6: *The average size (with standard deviation) of the front zone of personal space, related to the experimental procedures stop-distance A (personal space in static situations), approach-distance B (pedestrian personal space moving towards a stationary person) and locomotion-distance C (pedestrian personal space moving towards an oncoming pedestrian), tested at low, medium and high speed.*

The results achieved by means of the first presented experimental investigation (Section 6.2.2) showed that in situations of high density the turning path with 60° degrees had a significantly negative impact on pedestrian flow rate. This was 12% less flow rate compared to the egress path with 45° degrees and 17% less flow rate compared to the egress path with 0° degrees. The proxemic behavior of group members had a negative impact on walking speed within all scenarios considered in this study (0°, 45°, 60° and 90° degrees pathways). This was 9% lower than the walking speed of single pedestrians. Moreover, the angle path with 60° degrees had negative impact on the walking speed of both singles and group members (respectively 7% and 11% lower compared to the angle path with 45° degrees). In conclusion, an angle path with less than 60° degrees represents the maximum angle that does not reduce the pedestrian flow rate and walking speed in high-density situation.

The results achieved by means of the second presented experimental investigation (Section 6.3.2) showed that the size of the front zone of personal space in static situations is affected by walking speed: when approached at medium and high speed, subjects need to maintain a larger distance (95 cm in average), compared to low speed approach (72 cm), due to a fright reaction. Moreover, results showed that the size of the front zone of personal space while moving towards a stationary person (70 cm in average) is not affected by walking speed. This is similar to the one in static situations (low speed related), due to the subject' capability to estimate in time the required space to avoid spatial intrusion. Furthermore, the results about pedestrian personal space while moving towards an oncoming pedestrian showed that, in case of a reciprocal approach at high speed (1.46 m/sec), subjects need to maintain a larger distance (91 cm) compared to the one in static situations (low speed related). This is due to the need of an additional margin projected towards the direction of movement in order to anticipate in time the spatial intrusion of oncoming pedestrians.

Considering that the sample was composed of 17 Japanese, 2 Vietnamese and 1 Chinese, the achieved results encouraged future cross-cultural investigations about personal space and tolerance for spatial intrusion. Proxemic behavior depends indeed on the variability among subjects' culture Aiello (1987): in *high-contact cultures* (e.g., the Mediterranean, Arabic, Hispanic cultures) people exhibit closer distances during social interactions compared to *no-contact cultures* (e.g., Northern European, Caucasian American cultures) Hall (1966). Moreover, proxemic behavior in Japanese culture is characterized by a scarce acceptance for spatial penetrability during social interaction and, counter-intuitively, an high tolerance for spatial intrusion in situation of high density in public spaces (Iwata, 1992). For these reasons, the achieved results about personal space in static situations (low speed related) were compared with previous works already performed by using the stop-distance procedure (Hayduk, 1983): this showed that the size of the front zone of personal space in Japanese culture is larger than the one measured in Caucasian American culture (59 cm).

According to the proposed methodological approach, the achieved results represent a significant body of empirical evidences, aimed at defining descriptive set of metrics and parameters for characterizing pedestrian crowd dynamics. Although the experimental investigation of pedestrian personal space was focused on the spatial interaction between two-walkers, the achieved results represent an interesting contribution toward the definition a proxemic-based measure of density, linearly dependent on the subject's inability to avoid spatial invasion of personal space, both in static and motion situations. In conclusion, the proposed experimental investigations were finally aimed at supporting the improvement and validation of the simulation platform MAKKSim and the design of applicative strategies for a more efficient and safe management of pedestrian crowd dynamics.

Human Locomotion and Spatial Behavior	
Pedestrian Dynamics, Turning Path and Grouping	
Angle Path	the 60° degrees angle path is respectively 11.9% and 16.82% less flow rate compared to 45° and 0° degrees; it has a negative impact on the walking speed (9.37% lower compared to 45° degrees angle path)
Walking Speed	in high density situations the walking speed of group members is 8.9% lower than the one of single pedestrians
Pedestrian Personal Space	
Static Situation	when approached at medium-high speed, the front zone of personal space (95 cm) is bigger then low speed (72 cm)
Motion Situation	the size of the front zone of personal space while moving towards a stationary person (70 cm) is not affected by walking speed; in case of a reciprocal approach at high speed, the front zone of pedestrian personal space (91 cm) is bigger then static situations
Cultural Variability	the front zone of personal space in Japanese culture is larger than the one in Caucasian American culture (59 cm)

Table 6.5: *A synthesis of the results achieved by means of the experimental investigation of human locomotion and spatial behavior, with particular reference to the combined effect of turning path and grouping on pedestrian dynamics in high density situation, and the impact of walking speed on the size of the front zone of personal space.*

Acknowledgement

The presented experimental investigations have being respectively performed within the authorization of the Ethics Committee of the Monash University and The Tokyo University. The experimental investigation of pedestrian personal space has been funded by the Japan Society for the Promotion of Science. The results achieved by means the presented research efforts are respectively published in Gorrini et al. (2013) and already accepted for publication (Gorrini et al., 2014).

7

In Silico Simulation of Pedestrian Crowd What-if Scenarios

The Chapter presents several studies aimed at improving and validating the simulation platform MAKKSim (as presented in Section 7.2). The execution of a simulation campaign allowed to achieved empirical evidences about pedestrian crowd dynamics, focusing on different levels of density (LOS B and LOS D). The achieved results were compared with the data collected at the Vittorio Emanuele II gallery (Milan, Italy) (LOS B) (Seciton 7.3). Results showed that the group cohesion mechanism introduced in the model is effective, while quite similar outcomes have been achieved in relation to representation of heterogeneous walking path and speed among single pedestrians and group members. The Chapter ends with final remarks about the proposed methodological approach and on-going works.

7.1 Introduction

According to the proposed methodological approach, the Chapter presents several studies aimed at investigating pedestrian crowd dynamics by means of computer-based modeling and simulation activities. Thanks to the collaboration with the Complex Systems and Artificial Intelligence research center, the simulation platform MAKKSim was employed for the execution of a simulation campaign focused on the impact of grouping on pedestrian circulation dynamics in situation of variable density (LOS B and LOS D) (see Figure 7.4). The achieved results were compared with the data collected at the Vittorio Emanuele II gallery (Milan, Italy) (LOS B), in order to test the capability of the computational model of MAKKSim to represent group spatial dispersion and heterogeneous walking speed among singles and group members.

As mentioned in Chapter 4, pedestrian crowd models can be classified into three main categories that respectively consider pedestrians as: *particles* subjected to forces, particular states of *cells* and autonomous *agents* acting and interacting in a shared environment. The most widely adopted particle based approach is represented by the social force model (Helbing and Molnár, 1995), that basically represents the tendency of an agent to stay away from the others while moving towards its goal. In the framework of Cellular Automata approaches, the floor-field model (Burstedde et al., 2001) has been successfully applied thanks to the possibility to endow each cell with discretized gradients that guide pedestrians towards potential destinations. Lastly, the agent-based approach (Henein and White, 2005) essentially extend CA approaches, separating the pedestrians from the environment and granting them a behavioral specification that is more complex than what is generally represented in terms of a simple CA transition rule.

As pointed out in (Challenger et al., 2009; Schadschneider et al., 2009), there is still much room for innovations in pedestrians crowd models, improving their performances in representing the overall phenomenon both in terms of expressiveness and efficiency (e.g., simplifying the modeling activity, introducing the possibility of representing phenomena that are still not considered by existing approaches). In particular, one of the aspects that has been recently considered is the impact of grouping on pedestrian crowd dynamics. According the presented approaches, only few contributions have being focused on modeling groups of pedestrians, respectively in particle-based (Singh et al., 2009; Moussaïd et al., 2010), in CA based (Sarmady et al., 2009) and in agent-based approaches (Rodrigues et al., 2010; Tsai et al., 2011). In all these approaches, groups are modeled by representing the tendency of group members to stay close to the others during locomotion.

The software platform MAKKSim represents a step in this direction, thanks to the possibility to simulate pedestrian crowd dynamics by encompassing adaptive parameters for representing group spatial dispersion. In this schema, the agent-based model of MAKKSim is presented in Section 7.2, with reference to the representation of the simulated environment, the agent behavioral rules (e.g., goal-driven behavior, proxemic-driven behavior) and the preliminary validation of the model. The results achieved by means of a simulation campaign focused on the impact of grouping on pedestrian circulation dynamics in situation of irregular flows (LOS B and LOS D) are discussed in Section 7.3. The Chapter ends with final remarks about the proposed methodology for simulating pedestrian crowd dynamics and future developments of the simulation platform MAKKSim.

7.2 The Agent-based Computational Model of MAKKSim

The agent-based computational model of MAKKSim[1] (Bandini et al., 2001, 2009) represents pedestrians as multiple and heterogeneous agents with related perceptive and behavioral specifications (e.g., perceive and avoid spatial elements that represent obstacles, follow paths throughout environmental elements, perceive other agents) and the capability to interact in the shared environment in order to achieve some individual or collective goals (i.e. goal-driven behavior) (Bandini et al., 2004; Manenti et al., 2011,

[1] The computational model that sets the simulation platform MAKKSim is developed by using Python programming language. The MAKKSim graphic interface, that is needed to design the simulated scenario in which the agents are situated, is based on Blender, an open-source 3D computer graphics software.

2012). According to other studies (Was et al., 2006; Was, 2010), the representation of spatial interactions among pedestrians is based on a set of parameters for characterizing the dynamical regulation of distances among the agents and, in the same way, the tendency to maintain spatial cohesion among group members during locomotion (i.e. proxemic-driven behavior).

7.2.1 Simulated Environment

The simulation platform MAKKSim is based on modeling the environment in a discrete way. According to the observed average area occupied by a pedestrians in situation of low density (Weidmann, 1993), the simulated scenarios is represented as a grid of squared cells that are 0.4 meter long and 0.4 meter width. Cells have a state indicating if they are vacant or occupied by obstacles or by one or two pedestrians:

$$State(c) : Cells \rightarrow \{Free, Obstacle, OnePed_i, TwoPeds_{ij}\}$$

The information required for the execution of a specific simulation are represented by means of three kinds of *spatial markers* (i.e. special sets of cells that describe relevant elements in the environment): (*i*) starting areas, that indicate the generation points of agents in the scenario (agent generation can occur in block, all at once, or according to a user defined frequency), (*ii*) destination areas, that define the possible targets in the environment, (*iii*) obstacles, that identify the non-walkable areas (as walls and zones where agents can not enter).

The computational model of MAKKSim takes advantage from the *floor field* approach (Burstedde et al., 2001), that is based on the generation of a set of superimposed grids that contain space annotations and specific information. In particular, floor field values are spread on the grid as a gradient and they are used to support pedestrians in the navigation of the environment, representing their interactions with static objects (e.g., destination area, obstacle) or with other pedestrians. Moreover, floor fields can be static (created at the beginning and not changed during the simulation) or dynamic (updated during the simulation). Three kinds of floor fields are defined in the model: (*i*) path field, that indicates for every cell the distance from one destination area, acting as a potential field that drives pedestrians towards the target (static), (*ii*) obstacles field, that indicates for every cell the distance from neighbor obstacles or walls (static), (*iii*) density field, that indicates for each cell the level of density in the surroundings at the current time-step (dynamic).

7.2.2 Simulated Locomotion-Spatial Behavior and Grouping

The computational model of MAKKSim defined each agent by means of a numerical identifier, group membership (if any) and internal state: $Ped = \langle Id, Group, State\rangle$. In particular, the characterization of the internal state comprises the current position of the agent, the previous movement and final destination: $State = \langle position, oldDir, Dest\rangle$.

The model represents the locomotion-spatial behavior of the agents as organized into four steps: *perception, utility calculation, action choice* and *movement*. The perception step provides to the agent all the information needed for choosing its destination cell. In particular, if an agent does not belong to a group, it will only extract values from the floor fields, while in the other case it will perceive also the positions of the other group members in order to maintain spatial cohesion. The choice of each action is based on an utility value assigned to every possible movement according to the function:

$$U(c) = \frac{\kappa_g G(c) + \kappa_{ob} Ob(c) + \kappa_s S(c) + \kappa_c C(c) + \kappa_i I(c) + \kappa_d D(c) + \kappa_{ov} Ov(c)}{d}$$

Function $U(c)$ takes into account several components for the definition of the locomotion behavior of the agents[2]: $G(c)$ is associated to goal attraction, whereas $Ob(c)$ and $S(c)$ are respectively associated to geometric and social repulsion. Functions $C(c)$ and $I(c)$ are linear combinations of the perceived positions of group members in an extended neighborhood. $D(c)$ adds a bonus to the utility of the cell next to the agent according to its previous direction. $Ov(c)$ describes the overlapping mechanism, a method used to allow two agents to temporarily occupy the same cell at the same step, in order to represent high-density situations. The purpose of the function denominator d is to constrain the diagonal movements, in which the agents cover a greater distance (0.4 meter $*\sqrt{2}$, instead of 0.4 meter), assuming an higher walking speed compared with non diagonal paths.

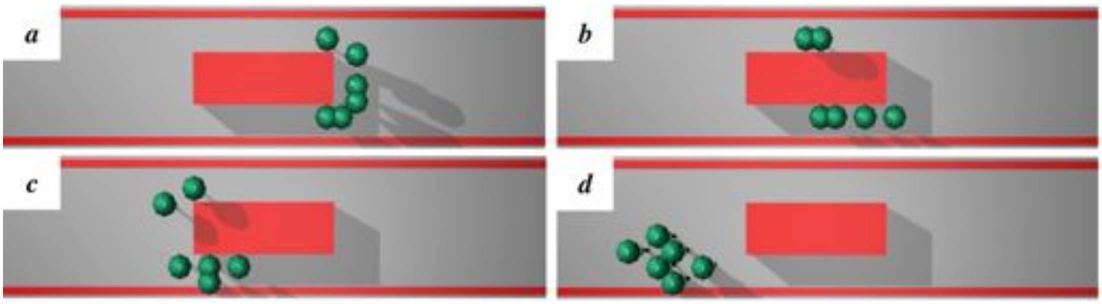

Figure 7.1: *The sequential snapshots a, b, c and d (extracted from the rendering of the simulations performed by using MAKKSim) illustrate the introduced group cohesion mechanism for representing the dynamic regulation of spatial distances among group members in case of an obstacle.*

The representation of groups of agents is based on the distinction between: (*i*) simple group, a restricted set of agents with a strong and recognizable spatial cohesion based on the tendency to stay close during locomotion in order to guarantee the possibility to interact, and (*ii*) structured group, a large set of agents with a slight spatial cohesion

[2]Each component is modeled with a function that returns values in range (-1,+1), if it represents an attractive element, or in range (-1, 0), if it represents a repulsive element for the agent. Moreover, each function is calibrated by using a coefficient κ.

and a common fragmentation into subgroups. In particular, functions $C(c)$ and $I(c)$ have been further defined in order to correctly model group spatial cohesion and to adaptively balance the temporary fragmentation of simple groups in front of spatial constraints (e.g., obstacles, oncoming pedestrians) (as illustrated in Figure 7.1).

The effective utility calculation employs calibration weights resulting from this computation, in order to represent group proxemic behavior: cohesion relaxes if members are sufficiently close to each other and it intensifies with the growth of dispersion. After the utility evaluation, the choice of action is stochastic, with the probability to move towards each cell c defined as: $P(c) = N \cdot e^{U(c)}$ (N is the normalization factor). In particular, on the basis of $P(c)$, agents move in the resulted cell according to the set of possible directions (plus the possibility to keep the previous position, that is indicated as X): $A = \{NW, N, NE, W, X, E, SW, S, SE\}$.

7.2.3 Preliminary Validation of the Model

The validation of computational models for simulating pedestrian crowd dynamics is made difficult by the lack of empirical evidences about the phenomenon, due to ethical and practical reasons. In recent years, several research efforts have been done to face this open issue. Set of data collected by means of both unobtrusive observation and experimental investigations are now available[3], allowing to compare results and define both quantitative and qualitative features that models have to be able to reproduce in order to be validated.

The most diffused criterion to evaluate the plausibility of a model is the so called *fundamental diagram* (Seyfried et al., 2005; Schadschneider et al., 2009), in which the relationship between the variation on the pedestrian flow with respect to the increasing of the level of density is represented. This validation method consists of employing already collected empirical results about the dependency between flow rate and density in order to evaluate the effectiveness of the model in representing the phenomenon: the pedestrian flow initially grows, since it is directly proportional to the density, until a certain threshold value is reached (i.e. critical density), then it decreases. Despite the fact that a model is able to reproduce the fundamental diagram, another criterion for validation is based on considering the capability of the model to reproduce plausible pedestrian circulation dynamics in terms of effective utilization of the space (e.g., lane formation, jamming in high density situations).

The computational model that sets the simulation platform MAKKSim has been already validated against the fundamental diagram and the space utilization criteria (Manenti, 2013). Unfortunately, the issue of group modeling appeared in the literature very recently, so data related to this phenomenon are very scarce. For this reason, the empirical evidences collected by means of the observation carried out at the Vittorio

[3]The open database PedNet (http://www.ped-net.org/) is one of the main resource of experimental contributions about pedestrian crowd dynamics, aimed at supporting the validation of computational models by using empirical evidences.

Emanuele II gallery represent a useful contribution towards the validation of the model, with particular reference to the introduced group cohesion mechanism.

7.3 The Case Study of the Vittorio Emanuele II Gallery

This Section is aimed at presenting the results achieved by means of a simulation campaign, focused on the impact of grouping on pedestrian circulation dynamics. Taking advantage from the unobtrusive observation performed at the Vittorio Emanuele II gallery (Milan, Italy) (see Chapter 5), the simulation activities started from the design of the 3D model of the inside volume of the gallery and its implementation into the software platform MAKKSim (see Figure 7.2). In analogy with the observed portion of the gallery, data analysis was focused on a corridor-like scenario (12.8 meter long and 12.8 meter width). At the North and South sides of the simulated walkway, both starting and destination areas have been placed for the generation of agents (respecting the frequency of pedestrian arrivals observed at the Vittorio Emanuele II gallery) and targets positioning.

In order to validate the introduced group cohesion mechanism among different levels of density, two pedestrian frequency profiles have been configured (i.e. number of pedestrians in the simulated environment at the same time): No. 40 pedestrians (LOS B: irregular flow in situation of low-medium density, 0.24 pedestrian per squared meter) and No. 96 pedestrians (LOS D: irregular flow in situation of medium-high density, 0.55 pedestrian per squared meter). According to the empirical data collected at the gallery, the agent population was composed of: 16% single pedestrians and 84% group members, divided in couples (52%), triples (20%) and groups of four members (28%). The simulation campaign was composed of a set of five simulations (5 minutes of simulated time, for a total of 25 minutes of simulated time) for each tested LOS conditions (LOS B and LOS D).

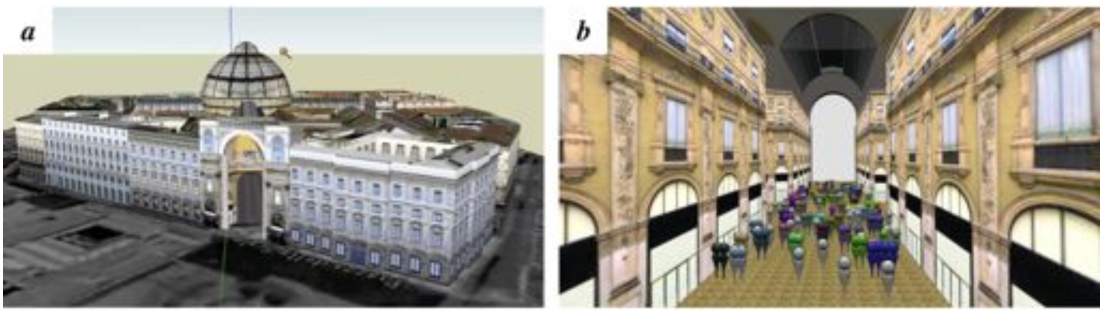

Figure 7.2: *As illustrated from the left to the right side: (a) the 3D model of the outside volume of the Vittorio Emanuele II gallery (Milan, Italy), designed by means of the open-source software Google SketchUp and then implemented in MAKKSim by using Blender, and (b) the 3D model of simulated scenario related to the inside volume of the gallery, with reference to the pathway and the situated agents.*

7.3.1 Results

Results (e.g., walking path and speed, group spatial dispersion) have been compared among them by means of two-tailed t-test analyses, considering LOS B and LOS D scenarios. The walking path and speed of agents have been detected considering the length of trajectories and the needed time to move from the start area to the destination area in the corridor-like scenario. The spatial dispersion among group members have been detected by using the centroid method (Bandini et al., 2011) (describing dispersion as the average distance assumed by members of the group from its center of gravity, calculated as the average position of all the group members).

Regarding LOS B, the sample was respectively composed of No. 6079 agents, divided in: 16% singles, 40% couples, 22% triples and 22% groups of four members. About LOS D scenario, the sample consisted of No. 11296 agents, as composed of: 16% singles, 42% couples, 18% triples and 24% groups of four members. Results were compared with the empirical evidences collected at gallery (LOS B), in order to validate the efficiency of the introduced group cohesion mechanism in representing the spatial dispersion of walking groups.

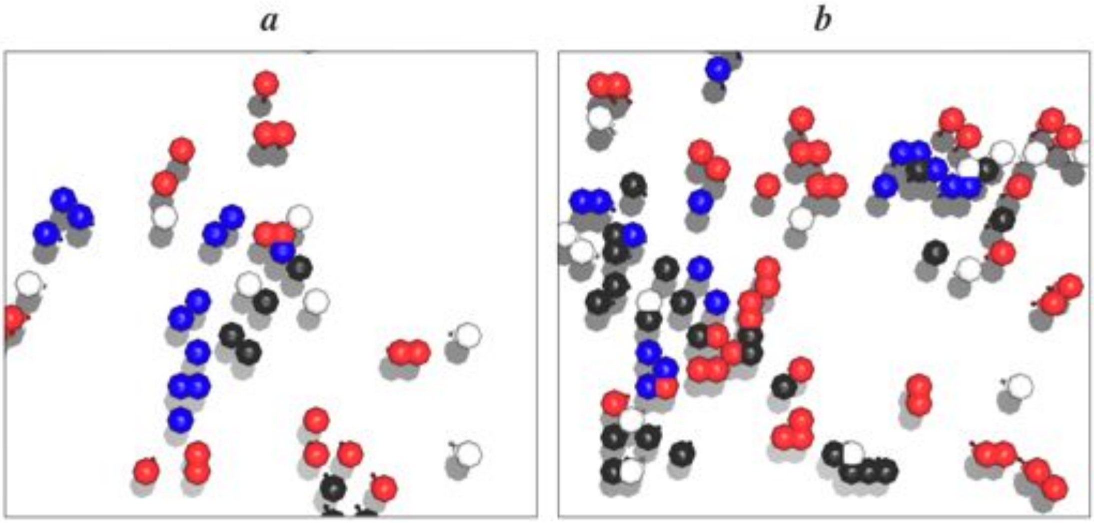

Figure 7.3: *As illustrated from the left to the right side, the snapshots extracted from the rendering of the performed simulation campaign, focused on pedestrian irregular flows in situation of (a) low-medium density (LOS B) and (b) medium-high density (LOS D), with reference to single pedestrians (white colored), couples (red colored), triples (blue colored) and groups of four members (black colored).*

Walking Path

Data analysis was focused on detecting the average length of the walking path of single pedestrians, couples, triples and groups of four members (see Table 7.1). Regarding LOS B scenario, the results achieved by means of two tailed t-test analyses showed a significant difference (p value<0.01) between the trajectories of singles and groups of two, three and four members, couples and groups of four members, couples and triples (p value<0.05). No significant difference (p value>0.05) between triples and four members groups. About LOS D scenario, results showed a significant difference (p value<0.01) between the path of singles and groups of two, three and four members, couples and triples, couples and groups of four members, triples and four members groups (p value<0.05).

In conclusion, results showed that the trajectories of single pedestrians within the tested LOS B and LOS D scenarios were respectively 1% and 3% less length than the path of group members (LOS B: 14.04 meter, sd 0.65; LOS D: 14.39 meter, sd 0.68). This is in contrast with the data collected at the gallery (LOS B), that showed that the average walking path of single pedestrians (13.96 meter, sd 1.11) was 4% longer than the one of group members (13,30 meter, sd 0.37).

	Group Size	**Simulated Path**	**Observed Path**
Level of Service B	Single	13.86 meter (sd 0.58)	13.96 meter (sd 1.11)
	Couple	13.99 meter (sd 0.63)	13.39 meter (sd 0.38)
	Triple	14.05 meter (sd 0.66)	13.34 meter (sd 0.27)
	4 Members	14.09 meter (sd 0.65)	13.16 meter (sd 0.46)
Level of Service D	Single	13.99 meter (sd 0.84)	-
	Couple	14.33 meter (sd 0.66)	-
	Triple	14.40 meter (sd 0.68)	-
	4 Members	14.45 meter (sd 0.69)	-

Table 7.1: *The average walking path (with standard deviation) of single pedestrians, couples, triples and groups of four members, related to the simulated corridor-like scenarios (LOS B and LOS D) and the data collected at the Vittorio Emanuele II gallery (LOS B).*

Walking Speed

Data analysis was focused on detecting the average walking speed of single pedestrians, couples, triples and groups of four members (see Table 7.2). Regarding LOS B scenario, results showed a significant difference (p value<0.01) between the average speed of singles and groups of two, three and four members. No significant difference (p value>0.05) among groups. About LOS D scenario, results showed a significant difference (p value<0.01) between the average speed of singles and groups of two, three and four members, couples and groups of four members, and couples and triples (p value<0.05). No significant difference (p value>0.05) between the average speed of triples and four members groups.

In conclusion, results showed that the walking speed of single pedestrians within the tested LOS B and LOS D scenarios were respectively 5% and 6% higher than the average speed of group members (LOS B: 1.22 meter/sec, sd 0.08; LOS D: 1.20 meter/sec, sd 0.08). This is quite in line with the data collected at the gallery (LOS B), that showed that the average walking speed of singles (1.22 meter/sec, sd 0.16) was 37% higher than the average speed of group members (0.77 meter/sec, sd 0.96).

	Group Size	**Simulated Speed**	**Observed Speed**
Level of Service B	Single	1.28 m/sec (sd 0.05)	1.22 m/sec (sd 0.16)
	Couple	1.22 m/sec (sd 0.08)	0.92 m/sec (sd 0.18)
	Triple	1.22 m/sec (sd 0.07)	0.73 m/sec (sd 0.10)
	4 Members	1.22 m/sec (sd 0.08)	0.65 m/sec (sd 0.04)
Level of Service D	Single	1.27 m/sec (sd 0.06)	-
	Couple	1.21 m/sec (sd 0.08)	-
	Triple	1.20 m/sec (sd 0.08)	-
	4 Members	1.20 m/sec (sd 0.08)	-

Table 7.2: *The average walking path (with standard deviation) of single pedestrians, couples, triples and groups of four members related to the simulated corridor-like scenarios (LOS B and LOS D) and the data collected at the Vittorio Emanuele II gallery (LOS B).*

Further two-tailed t-test analyses were carried out in order to compare LOS B and LOS D scenarios, testing the impact of density on walking path and speed. Results showed a significant difference (p value<0.01) between the average walking path and speed of singles, couples, triples and group of four members related to LOS B and LOS D scenarios. In conclusion, results showed that the average speed of singles and group members within LOS D scenario were respectively 1% and 2% lower than the speed of singles and group members within LOS B scenario.

Group Spatial Dispersion

Data analysis was focused on detecting the average spatial dispersion of group members (see Table 7.3). Regarding both LOS B and LOS D scenarios, results showed a significant difference (p value<0.01) between the average spatial dispersion of couples and triples, couples and groups of four member, triples and groups of four members. In conclusion, results showed that the average spatial dispersion of couples within the tested LOS B and LOS D scenarios were respectively 38% and 36% lower than the average dispersion of groups of three and four members (LOS B: 0.60 meter, sd 0.30; LOS D: 0.59 meter, sd 0.19). This is in line with the data collected at the gallery (LOS B), that showed that the average spatial dispersion of couples (0.35 meter, sd 0.14) was 42% lower than the ones of group of three and four members (0.60 meter, sd 0.14).

Further two-tailed t-test analyses were carried out in order to compare LOS B and LOS D scenarios, testing the impact of density on group proxemic behavior during locomotion. Results showed a significant difference (p value<0.01) between the average spatial dispersion of couples and groups of four members related to LOS B and LOS D scenarios. No significant difference (p value>0.05) between the spatial dispersion of triples within LOS B and LOS D scenarios.

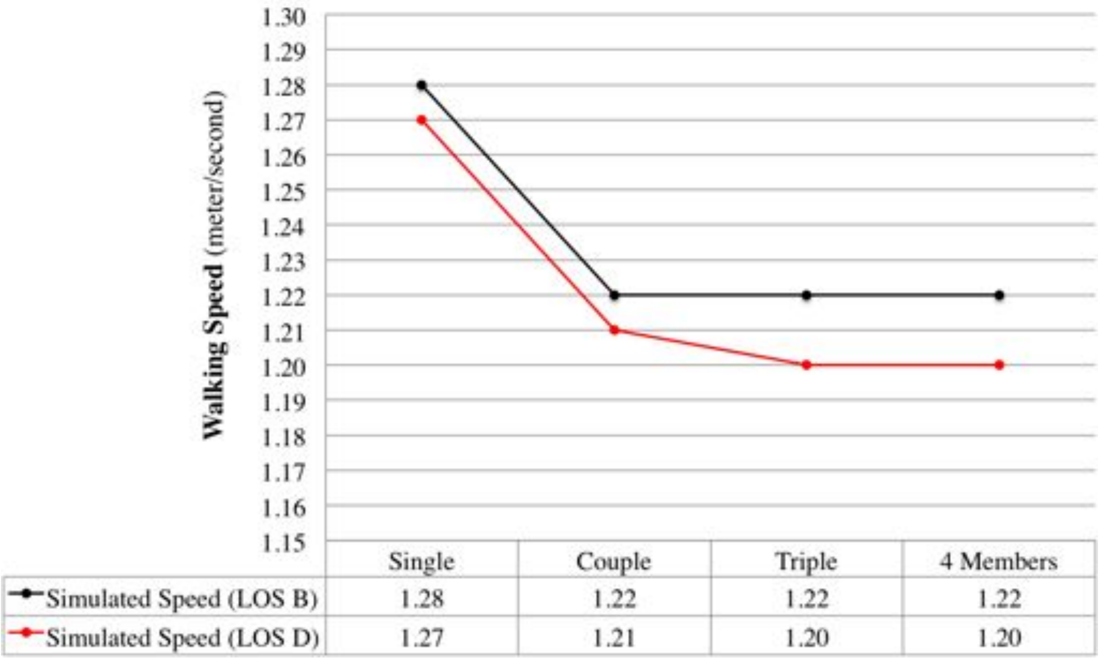

Figure 7.4: *The average walking speed of single pedestrians, couples, triples and groups of four members, with reference to the tested LOS B (low-medium density) and LOS D (high-medium density) scenarios.*

	Group Size	Simulated Dispersion	Observed Dispersion
Level of Service B	Couple	0.37 cm (sd 0.19)	0.35 cm (sd 0.14)
	Triple	0.54 cm (sd 0.22)	0.53 cm (sd 0.17)
	4 Members	0.67 cm (sd 0.38)	0.67 cm (sd 0.12)
Level of Service D	Couple	0.38 cm (sd 0.19)	-
	Triple	0.54 cm (sd 0.20)	-
	4 Members	0.65 cm (sd 0.19)	-

Table 7.3: *The average spatial dispersion (with standard deviation) of couples, triples and groups of four members related to the simulated corridor-like scenarios (LOS B and LOS D) and the data collected at the Vittorio Emanuele II gallery (LOS B).*

7.4 Final Remarks

The Chapter presented the results achieved by means of a simulation campaign, aimed at investigating the impact of grouping on pedestrian crowd dynamics. The empirical evidences achieved by means of the unobtrusive observation carried out at the Vittorio Emanuele II gallery (Milan, Italy) were employed towards the validation of the agent-based computational model of MAKKSim, focusing on the introduction of a specific adaptive mechanism for characterizing group spatial dispersion during locomotion. The achieved results (e.g., walking path and speed, group spatial dispersion) have been compared considering two simulated scenarios with different levels of density (LOS B and LOS D).

Results showed that the group cohesion mechanism introduced in the model is effective. The spatial dispersion among group members in situation of irregular flow is consistent with reference to the tested scenarios (LOS B and LOS D) and the empirical evidences achieved at the gallery (LOS B). In particular, results showed that within the simulated LOS B scenario couples walked about 38% less disperse than groups of three and four members.

On the other hand, the computational model is able to reproduce quite similar outcomes on walking speed, compared to the data collected at the gallery. In particular, results showed a slight difference between the speed of single pedestrians and group members within the simulated LOS B and LOS D scenarios. This is due to the fact that at this stage all the agents are configured with the same speed[4] (1.3 meter/sec), typical observed in pedestrians dynamics for business purposes (Schultz et al., 2010). On the contrary, the pedestrian circulation dynamics observed at the gallery were characterized by a lower group speed due to the leisure purposes while crossing the space (e.g., shopping, entertainment, visiting touristic-historical attractions). This aspect had an impact also on the travel distances covered by pedestrians in the simulated scenario: the trajectories of individuals were less length than the ones of group members, unlike in the observed data. Moreover, it has to be noted that the discrete model of MAKKSim has intrinsic limits in the faithful reproduction of trajectories (that are inherently jagged and not as smooth as the real ones), so it could be difficult to improve this kind of result adopting a discrete model.

In conclusion, the presented simulated campaign allowed to achieved several empirical results about the impact of grouping on pedestrian circulation dynamics, generally in tune with the data collected at the gallery. However, the performed validation phase showed that the computational model of MAKKSim has some limitations in representing heterogeneous walking speed among single pedestrians and group members. For this reason, a more detailed calibration of the model is needed in order to represent this phenomenon (e.g., different classes of pedestrians associated to different walking

[4]The computational model of MAKKSim is based on a discrete definition of the duration time steps (0.31 seconds). This choice, considering the size of the squared cells, generates a linear pedestrian speed of about 1.3 meter/sec.

speeds), considering a stochastic mechanism that ensure the maintenance of an average speed close to this threshold.

Further simulation campaigns are going to be carried out in order to validate the computational model of MAKKSim, facing the empirical evidences achieved by means of the previously presented unobtrusive observations and experimental investigations (see Chapter 5 and Chapter 6). In this schema, future works will be focused on testing the impact of the introduced group cohesion mechanism on pedestrian crowd what-if scenarios characterized by different physical layouts (e.g., corner-like scenario) and variable levels of density (see Fig. 7.5).

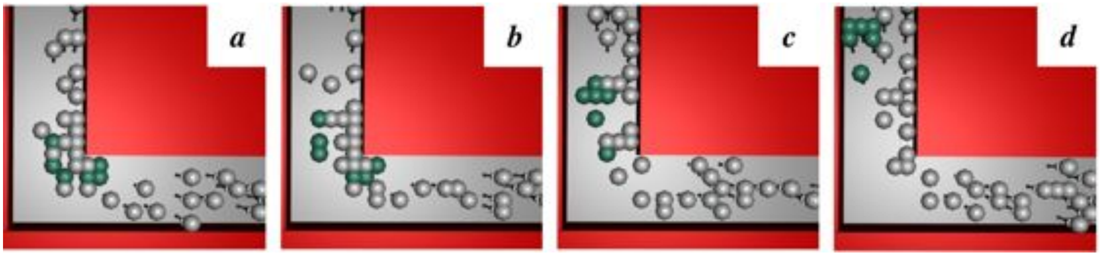

Figure 7.5: *The sequential snapshots a, b, c and d, extracted from an on going simulation campaign performed by using the software platform MAKKSim, focused on the impact of grouping on pedestrian circulation dynamics in a bidirectional corner-like scenario.*

Acknowledgement

This work has been performed thanks to the fruitful collaboration with the Complex Systems and Artificial Intelligence research center. The computational model of the simulation platform MAKKSim is described in details in Bandini et al. (2011). The results achieved by means of the presented simulation campaign are published in Bandini et al. (2013).

8 Conclusions and Future Works

Thanks to the proposed interdisciplinary approach (e.g., social science, computer science, traffic engineering, applied mathematics and urban planning), the current thesis work included several studies aimed at empirically investigating pedestrian crowd dynamics. This was intended to achieve descriptive set of metrics and parameters for characterizing the phenomenon and support the improvement and validation of computer-based pedestrian crowd models and simulations.

The novelty of this work is twofold. From a theoretical perspective, the review of the social science framework showed that since the pioneering study of Gustave Le Bon (1897) the definition of the crowds is still controversial. For this reason, the research effort was focused on the analytical investigation of pedestrian dynamics in situation of variable density. This was based on the extension of the general framework of *proxemics* (Hall, 1966), in order to characterize human spatial behavior during locomotion (considering both individual and group level of investigation).

Then, the proposed methodological approach was based on the innovative integration among: the *in vivo* observation of pedestrian circulation dynamics in urban crowded scenarios, *in vitro* experimental investigation of human locomotion and spatial behavior in laboratory setting, *in silico* simulation of pedestrian crowd what-if scenarios. In this respect, the work was aimed at testing the impact of proxemics (e.g., pedestrian personal space, group spatial arrangement and dispersion), grouping (i.e. the basic interacting elements that compose a crowd) and density (e.g., competitive interactions among pedestrians in crowded environments) on pedestrian crowd dynamics (e.g., flow rate, trajectories, walking speed).

The results achieved through the presented observations (Section 5.2.2 and Section 5.3.2) showed that it is crucial to take into account the impact of grouping on pedestrian crowd dynamics, considering the massive presence of groups within the observed pedestrian flows. Moreover, results showed that the size of groups has a negative impact on both walking path, speed and spatial dispersion, due to the need of members to maintain spatial cohesion during locomotion. The results achieved by means of the proposed experiments showed that an angle path with less than 60° degrees is the maximum angle that does not reduce the flow rate and walking speed of both singles and groups in high density situations (Section 6.2.2). Furthermore, results showed that the size of pedestrian personal space is bigger then the one in static situations, due to the need of an additional margin projected ahead in order to anticipate the spatial intrusion of oncoming pedestrians (Section 6.3.2).

Thanks to the fruitful collaboration with the Complex Systems and Artificial Intelligence research centre, the collected empirical evidences have been applied to validate the simulation platform MAKKSim (Section 7.3), checking the capability of the model to generate similar outcomes to the ones produced by the target. The statistical data obtained by means of the execution of a simulation campaign showed that the computational model of MAKKSim is effective in representing group spatial dispersion during locomotion, thanks to the introduction of a specific adaptive mechanism for characterizing group cohesion. Moreover, the model is able to reproduce quite similar outcomes related the observed heterogeneous walking speed among single pedestrian and group members.

The results achieved by means of both observations, experiments and simulations represent an extremely interesting and significant body of empirical data, that is currently being applied for sake of model innovation and validation. Further simulation campaigns are going to be performed, focusing on those situations in which the results are not actually in good agreement with the collected empirical evidences.

Then, in a circular process, further on field observations will be focused on pedestrian crowd dynamics under a variety of circumstances, considering the possibility to employ automated techniques for data collection (Jacques Junior et al., 2010), thanks to the wide diffusion of cameras used for video surveillance of public areas and the level of maturity of video processing and analysis techniques. Moreover, a set of on going experimental studies have been already designed in order to investigate the capability of social variables, such as groups, to mitigate the effects of crowding during locomotion in high density scenarios[1], by producing spatial boundaries that shield group members from unwanted interactions and rise the capability to communicate among them.

Future works will be also aimed at supporting a substantial improvement of the computational model of MAKKSim. At this stage, the model is based on the representation of *reactive agents*: autonomous and situated entities, characterized by elementary behavioral and perceptive specifications. The agents behavior are related to the capability to perceive the stimuli coming either from other agents or from the environment, and finally driven by a set of behavioral rules. Future modeling activities will be focused on *cognitive agents* (Wooldridge et al., 1995): deliberative entities, characterized by a more complex action-selection mechanism based on logic reasoning. This approach is based on representing agents knowledge about the environment and on memories

[1]The proposed on going procedure consists of grouping participants and asking them to walk freely according to the situation of high density in the experimental setting. The subjects' level of salivary cortisol (a lipophilic steroid produced by the adrenal cortex) is measured by using a synthetic swab, as an accurate indicator of endocrine and hypothalamic neural activities related to physical and psychological stressors, such as crowding (Baum and Paulus, 1987).

of past experiences. This improvement would permit to simulate pedestrian crowd dynamics considering more complex lines of social action (e.g., group way-finding activity in case of emergency evacuation), based on agents strategic-tactical reasoning skills and proactive behavior (Schadschneider et al., 2009).

In conclusion, the presented research effort was aimed at supporting the design of applicative strategies for a more efficient and safe management of pedestrian crowd dynamics during large urban events (e.g., sizing the number of ticket offices and gates, in order to avoid queues or disruptions during the entrance and exit processes from a venue) and mass gathering-transit facilities (e.g., sizing the physical layout of walkways and egress routes, in order to facilitate pedestrian circulation dynamics). This represent an on going work, based on the further interpretation of the results achieved by means of the presented studies, in addition to empirical investigations that will be performed in the future (considering both observations, experiments and simulations).

For instance, according the European Charter for pedestrians' rights (1988), pedestrians have the right to live in a healthy environment and to enjoy freely the amenities offered by public areas, under conditions that adequately safeguard their physical and psychological well-being. In this regard, the proposed integrated approach is aimed at supporting the sustainable design of urban crowded scenarios (Whyte, 1980), guaranteeing the accessibility and *walkability*[2] of public spaces also for people with impaired mobility (Gehl, 1987). In conclusion, the proposed thesis work represents a starting point for future interdisciplinary studies aimed at developing architectural solutions, applicative guidelines and policies for supporting the improvement of the spatial efficiency of potentially crowded facilities, both in terms of service, comfort and safety.

[2]The term *walkability* (Gehl, 1987) refers to a measure of how friendly an urban area is for pedestrians (e.g., absence and quality of footpaths and sidewalks, traffic and road conditions, safety of crosswalks).

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