Understanding crowd behaviour

Wijermans, Ferdinanda Elfrida Hubertina

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Understanding Crowd Behaviour

Simulating Situated Individuals

Nanda Wijermans

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Promotor:	Prof. dr. R.J.J.M. Jorna
Copromotores:	Dr. W. Jager Dr. A.J. van Vliet
Beoordelingscommissie:	Prof. dr. R.J.F. van Haren Prof. dr. B.G. Silverman Prof. dr. K.G. Troitzsch

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Chapter 1

Introduction

[August 22 2009, Hoek van Holland] It is 18:00hrs, with the sound of music the beach party starts. Like previous years, this Saturday is the evening that the beach festival takes place. However, this evening will take a different turn.

Visitors arrive at the site by public or private transport. The site is becoming increasingly more crowded and at 21.00 people are still arriving in large numbers[1]*. Usually, different artists perform at a variety of stages; people cluster together in front of the stage while dancing, others queue up for the use of toilets and bars, or stand together while drinking a beer. This is a typical snapshot of people's behaviours at a festival.*

Among the partying visitors another group can be identified: hard-core-football supporters. The 'supporter' group forms and grows. While the majority of festivalgoers enjoy their evening, some of them experience a change in atmosphere [between 21.00 and 22.30 hours]. Suddenly, agitation develops as some from the supporter group recognise some plain-clothes law enforcement officers (henceforth LEOs). Initially 2, and later 4 LEOs are surrounded, and subjected to verbal and physical abuse. The LEOs retreat, but are chased by an aggressive group of unknown composition. During this time the LEOs receive back-up, and now number 45 LEOs; the aggravating group has also increased in size, totalling between 200-300 people. The situation continues to be hostile; the group starts a countdown - some warning shots are fired by the LEOs, yet the hostilities continue.

The LEOs retreat even further away from the site of the initial tensions by using an emergency exit into the dunes. Although the aggressors are initially halted by the fences, they tear these down and continue their pursuit of the LEOs. All kinds of objects are thrown at the LEOs: bottles filled with sand, planters and bikes, accompanied with continued verbal abuse. The situation escalates, and LEOs fire more warning shots, but again this fails to calm the situation. Some of the LEOs then fire targeted shots aiming at individual's legs. This leaves 6 people injured and one person mortally wounded. Mounted police arrive at the scene. After they have charged three times the aggressive group disperses and the LEOs are 'released' from their precarious position. The festival is stopped. The public are told that a minority spoiled the evening for everybody. Many

[1] The number of people present this evening cannot be determined. The visitor amount was estimated between 25.000-50.000 people.

Box 1. Shopping

A typical shopping main street is crowded with people. Most people walk on their right side, resulting in two streams: upwards and downwards. Most of the people walk in small groups with their family, friend(s) or partner, but some walk alone. Shoppers wander through the streets and enter the shops of their preference. From a distance the street looks crowded, and the composition changes all the time as people are arrive, shop and leave, a continuous in and outflow until closing time.

Box 2. Supporting a sports team

Crowd behaviour at a football match starts well before the match. Fanatic supporters gather around the stadium, eat snacks and hang out together. Sudden yells and gestures mark the arrival of supporters of the opposing team. The stadium is open now, people stand in line to enter the building and to find their seats. As soon as the game starts the supporters gaze in the direction of the field in front of them. The public reacts to whatever happens during the match. One can hear a lot of oohh's, ahh's, clapping and singing. But there is also yelling, chanting and gesturing as a provocation or response to the rival supporters.

people, who did not know what had happened, felt that the party ended too early[2].

This thesis sets out to gain more understanding of crowd phenomena, just like the one that was just described. The situation described above contains several examples of crowd behaviour. Crowd behaviour exists in a broad range of situations. Shopping on a main street, supporting a sports team at a match and people demonstrating are all typical examples. Boxes 1 - 3 illustrate different crowd events. In talking about crowds a variety of words can be used to describe the atmosphere, such as calm, excited, hostile, grim, threatening or dangerous. During an event, behaviour varies over time, but behaviour can also differ quite a lot between events. For example, an emergency context (in which people flee) differs considerably from a riot situation (in which some people behave violently). Regardless of the diversity of behaviour, all these events concern behaviour of a large number of people that are physically present at a certain location.

The beach festival example raises a variety of questions about the nature of crowd behaviour. Crowds events occur every day, so what causes this one to turn into a riot? Furthermore, the violent behaviour was conducted by a small part of the crowd. Why did the others not behave this way? How can these violent situations be prevented? Or, when things have already escalated, how can one effectively intervene? What are the processes leading to escalation?

Typically, the attention of the media focuses on crowds that show the most striking, and unique behaviours or on crowds that show behaviour which is generally considered to be undesirable (e.g. the hostilities towards the LEOs at the beach festival). However, there is much more to crowds than striking or undesired behaviour. At the beach party, apart from the 200-300 persons involved in hostilities, the other 25.0000

[2]Source: Rapport Hoek van Holland (Muller, Rosenthal, Zannoni, Ferwerda, & Schaap, 2009; Wanders, 2009).

Box 3. Emergency

Crowd behaviour in an emergency situation involves a large group during dangerous circumstances. Events at the Love Parade on 29th of July 2010 in Duisburg may serve as an example. One and the same way served as both entrance and exit. The end of one activity (the parade) and the start of another activity (live-gigs) caused large streams of people moving away from and towards the festival area. At that moment it is estimated that 130.000 people were present. The density of people at the location where the ingoing and outgoing streams met became extremely high. The movement of individuals was severely restricted, and in the end most movement was the result of physical pressures rather than individual decision-making. People situated at the sides attempted to flee by climbing light-poles and a small staircase that was initially blocked by police. However, most people could not move and endured high pressures that caused an anxious and deadly situation. In the end 19 persons died as a result of suffocation and 342 got wounded. According to panic-researcher M. Schreckenberg the catastrophe was the inevitable outcome of physical factors (WDR, 2010b). [source: (WDR, 2010a; Dettweiler, 2010; Team, 2010)]

people present at the beach festival engaged in 'normal' festival behaviour (for further reading consult the evaluation report (Muller et al., 2009) and newspaper articles, such as (Wanders, 2009)).

In the beach festival example, people in a crowd exhibit behaviour that changes all the time. For instance, let us zoom in on a person in front of the stage: let's call him[3] J*. First J* dances in front of the stage; then he walks to the bar, later he drinks beer and chats with his friends. Crowd behaviour is not uniform or static; it differs per person and changes over time. Zooming back to a group perspective, patterns emerge within the crowd, i.e. regularities in the form of movements and other types of behaviour can be observed. J* takes part in several typical crowd patterns, see figure 1.1 (a, b, c and d). While dancing, J* and the other people in front of the stage form an *arc-shaped* pattern (figure 1.1b). At a later point in time a pattern within the *lanes* of movement can be seen (figure 1.1c), when J* and others are heading to the bar. Even while talking to his friends J* forms a part of a pattern: the *companion clusters* of people that are standing close together or moving at the site (figure 1.1d).

In addition to the crowd patterns that J* forms a part of, the group which acts violently towards the LEOs, and the LEOs themselves, form patterns from their distinct behaviours. Acting in a similar way, such as drinking beer, is considered a behaviour pattern. Hence, a behaviour pattern is not restricted to actions involving movement. The hostile group displays aggressive behavioural patterns by shouting and throwing objects at the LEO's. These behavioural patterns arise in addition to those which are visible due to movement of the supporter group by surrounding the LEOs (i.e. an *arc* or *ring*-shaped pattern), or by chasing the LEOs that are retreating (i.e. *lanes*). Additionally, the LEOs themselves form a behaviour pattern as a result of retreating

[3]This thesis occasionally uses "he", "his", or "him". The male form was chosen as an act of gallantry towards the opposite sex, but refers to both sexes.

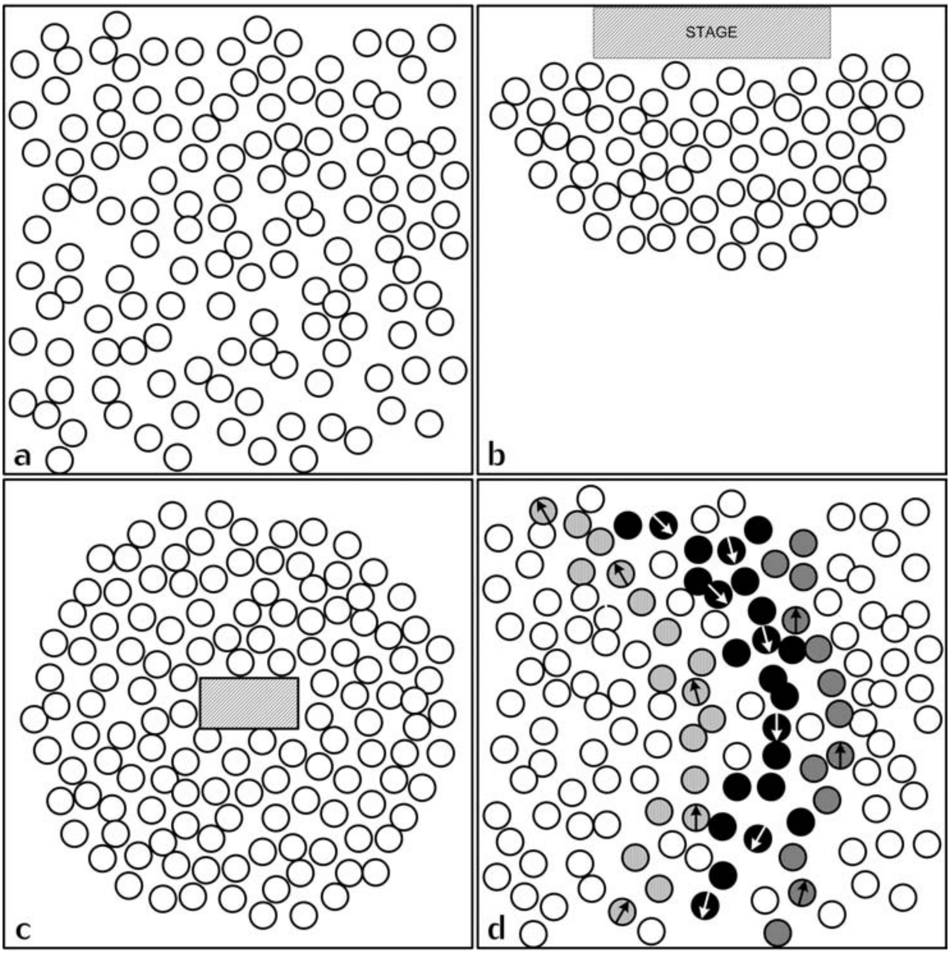

Figure 1.1: An overview of some typical behaviour patterns shown in crowds: a) Companion clusters, b) Arcs; c) Rings and d) Lanes.

and clustering together.

These behaviour patterns are an aggregate of the behaviour individuals display. The patterns show behavioural diversity, they are dynamic and vary in size, duration and composition. These emergent patterns of behaviour usually draw attention, especially if the behaviour is considered to be deviant or if it occurs unexpectedly. The patterns link people in a crowd based on the behaviour they show. They represent a dynamic notion of the changing subgroups within a crowd. The question may be raised how these patterns come about and what information can be derived from the patterns in order to facilitate the effective management of crowds?

1.1 Why is understanding crowd behaviour important?

Societies have various ways of managing crowds and behaviour. For instance, the LEOs deal with crowds by maintaining public order, event organisers provide entertainment and transporters provide mobility at airports and train stations. These organisations should take into account the way that crowds behave. But do they know how people will behave? What affects or steers crowd behaviour? What determines whether a potential riot is emerging? Or in what way people will flee in case of an emergency? And, when using a preventive measure, to what degree can the impact of such be known?

To improve safety and public order issues in crowds, practical experience is the main guide and source of knowledge for practitioners (Adang, 2006). The advantage of experience-based knowledge is that it is usable, goal-oriented, fast and implementable. A good intuitive feeling about a crowd situation and how to deal with it is important, and practically valuable, but within unclear boundaries. It is difficult to make implicit knowledge explicit and transferable, which implies it is hard to learn or to teach. In addition, it is difficult to test whether implicit experience-based knowledge is valid. And importantly, experience-based knowledge is situation specific, the usefulness in an even slightly different crowd situation is not clear. Experience-driven knowledge does not involve general understanding or explanation of the phenomenon of crowd behaviour itself.

Science aims at understanding and explaining a phenomenon (i.e. by gaining systematic knowledge). Existing crowd research has its limitations: there is a strong focus on disorder where the role of the social context is stressed. Generally, the methods used to study crowds are observation, post-hoc reviews of incidents and media-analysis.

The theories which underpin crowd research have developed significantly since the 1800s. For now, it is important to note that the historical path which crowd researchers have followed may have constructed misconceptions (i.e. myths, about crowds and their supposedly extraordinary behaviour). For example, for a long time the most dominant and popular view on crowds was the supposed existence of a *'group mind'*. The idea of a group mind refers to individuals losing cognitive control when entering a crowd and behaving at the will of this group mind (LeBon, 1895).

In the last 20 years significant advances have been made in the field of crowd research. Observational studies have challenged the dominating myths and major insights have been gained that provide the the foundations of modern crowd research. Chapter 2 describes this in detail. The main insights indicate that contrary to previous perspectives crowd behaviour is affected and generated by individuals; is situation dependent; is a social and dynamic phenomenon. Despite the advances, the current state of crowd research does not provide systematic knowledge or testable theories that allow a full explanation or understanding of crowd behaviour. This knowledge-gap results from both theoretical and methodological causes.

1.1.1 Theoretical issues in understanding crowd behaviour

Current theory of crowd research is fixed on disorder with an explanation that stresses the social context. To cover crowd behaviour in general, the current focus and the level of detail that is used to explain crowd behaviour from a mono-disciplinary perspective is not sufficient.

Disorder is a specific situation that typically involves a part of the crowd behaving confrontationally or violent. In addition to the fact that most crowds are not violent, it is not this specific behaviour (violence) that will help to achieve a general understanding of behaviour in crowds. For that, it is important to distinguish between specific behavioural outcomes and general mechanisms that give rise to crowd behaviour.

The role of the social context on the other hand has been shown to be crucial. However, the social context is not the only influence on behaviour, as crowd behaviour is situation dependent. For instance, the physical environment (e.g. a fence, or wall) and the internal (or cognitive) state of a person (e.g. being thirsty or afraid) also influence behaviour. The role of influence factors are not constant, they are variable. Let's go back to J* dancing in front of the stage. J* is surrounded by other people that are certainly part of his social environment. His local social surrounding affects J* as he enjoys being part of a huge group at a beach festival. J* likes it even more because his friends are dancing next to him. The people around J* are also physical objects that affect J* just by being obstacles or pushing forces that cannot be neglected in explaining J*'s behaviour. In addition to J*'s external situation, he also has an internal world where he notices he is thirsty which, at some point in time, makes him decide to move towards the bar. The fact that he enjoys this particular scene is a personal preference. This example illustrates the continuous interplay between external and internal factors that give rise to the behaviour of an individual in a crowd (i.e. situatedness). One second the role of the social environment might be important, and in the next, physiology and/or mental states might be more important.

In understanding crowd behaviour in general, the level of detail used in a theory defines the explanatory power. Although current theories acknowledge the individual as the atom of behaviour generation, the level of detail to explain the generation of individual behaviour does not describe *how* and *why* individual behaviour is chosen. Take for example, the situation that J* is going to the bar because he is thirsty. When the internal state of J* is not 'externally accessible' for this kind of information, it may well be that he is moving to the bar because he wanted to be social and join his friends (and not because he needs a drink). The behaviour J* shows is not explaining why he acts the way he does[4]. This information is crucial to gain understanding of individual behaviour and thus of crowd behaviour patterns. Regarding individuals as black boxes limits the explanatory power to understand why certain behaviour is chosen at a particular time and a given internal setting, and consequently this restricts the explanation of behaviour patterns.

Crowd research is, like most of the social sciences, usually approached from a mono-disciplinary perspective. Hence, the focus and way of explaining crowd behaviour is related to the scientific field the researcher is from. Despite the insight that

[4]Not only does this give insight in the reason for acting this way, it also says how an individual is influenced. For instance by observing someone else a 'false' attribution can be made and consequently the behaviour is influenced.

crowd behaviour is situation dependent, this is not incorporated when research disciplinary boundaries are reached. In this thesis, crowd behaviour research is regarded to typically need a broader scope. Not only because of the diversity of the behaviour it should encompass, but also because the relevant aspects that affect human behaviour originate from both the external (physical and social factors) and internal (physiological and cognitive) world. Studying crowd behaviour in general is too broad to neglect the other communities. The selection of relevant elements should be based on the question at hand, instead of on the discipline or the method used.

In summary, current theories are too narrow and specific scope, while providing little detail in describing human behaviour which can be used to develop testable general theories that allow to understand general behaviour dynamics. Modern crowd research forms the fundamental base for the work done in this thesis.

1.1.2 Methodological issues in understanding crowd behaviour

Theoretical progress in understanding crowd behaviour is mainly hindered due to the methodology that is used. In crowd research a variation of instruments is used, for example media analyses, case-studies, *backward study of incidents*[5], interviews and observation studies. Observation studies are currently the main research tool used in crowd research. However, in moving further from description to explanation, the difficulty of performing controlled experiments form the biggest constraint on progress in crowd research.

This limitation arises from the nature of crowd phenomena. Crowds are typically complex and dynamic phenomena, which means that a multitude of (interconnected) factors can play a role in the behaviour that emerges over time. This multitude of factors is hard to control for, when performing experiments. It is this methodological restriction that stagnates the formation of testable theories. Without experiments, generating an empirically based explanation of how and why crowd behaviour patterns emerge is difficult.

In addition to the difficulty of controlled experiments, there are also ethical considerations - it can be dangerous for the subjects. Performing experiments might be possible for smaller groups concerning behaviour that does not cause high pressure levels or violence. But for most crowd situations pressure levels are part of the phenomenon. In addition to that, the focus on disorder is driven by a need to prevent and manage disorder. But experimentation in a disorder setting is not possible as the well-being of the subjects cannot be guaranteed in such an experiment[6]. Consequently, it is almost impossible to experimentally test theories and thus take the necessary steps to understand and explain crowd behaviour.

An increased understanding, based on a body of systematic knowledge would enhance the ability of authorities to prevent undesired situations and to intervene in

[5]The described beach festival riot is an example of this backward study. After an incident took place a research is set up to investigate the cause and responsibility of the escalation (Muller et al., 2009).

[6]In addition to a few exceptional cased done by the research institute TNO during military training (van Vliet & de Bruin, 2007; Bruinsma-Jakobsen, 2007) and training of the riot police (Wetzer, Kamphuis, van Hemert, in 't Veld, & Kerstholt, 2010) and the police academy in The Netherlands (Bruinsma-Jakobsen, 2007).

them. Similarly, in crowd research, this development would be a huge step forward by explaining why and how crowd behaviour emerges, by moving beyond observation based studies. The current state of the crowd research indicates two issues: the need for a generic testable theory and the need for a methodology. First, there is a need for a testable theory that explains why and how behaviour patterns emerge. Secondly, a method is required that allows theories of crowd behaviour to be tested. In this thesis the focus lies on both issues by developing a crowd model using an integrative, multi-level and situated approach that is explored by performing computer simulation experiments.

1.2 Understanding crowd behaviour

To understand crowd behaviour it is important to explain why and how crowd behaviour patterns emerge. To be more specific, this thesis tries to answer the general research question:

> Which mechanisms underlie crowd behaviour patterns?

By resolving these theoretical and methodological issues this thesis takes significant steps to answer the research question. The mechanisms represent general rules that describe the way crowd behaviour patterns form and change. Consequently, both theory and methodology need to support the ability to explain why and how crowd behaviour emerges. Modelling crowd behaviour from a general perspective combined with an approach that integrates relevant theories and influence factors, should allow for a general understanding of how a situated crowd is realised. With use of a simulation, the model can be explored and tested by setting up simulation experiments. The combination of an integrative approach in modelling and the use of simulation experiments is expected to provide the necessary ingredients for understanding crowd behaviour.

The model that was developed is CROSS, a model that represents crowd behaviour that simulates situated individuals. In developing the model the following choices were made: the model focuses on explaining crowd behaviour in general rather than specific behaviours, such as violence or fleeing. The base of the CROSS model is formed by the main insights gained by current crowd research: the individual-level of agency, the role of (social) context and the dynamic nature of crowd behaviour. Crowd behaviour patterns are a property of the group level description of a crowd. However, to explain this group level property it is necessary to include the level at which behaviour is generated, i.e. the individual level. This makes understanding crowds a typical project with a multi-level approach.

In the model, the role of the context comes about by incorporating the relevant factors of the physical and social environment, as well as the individual internal properties, which involve a merger of multiple relevant theories. These dynamics represent the interactive properties of crowd behaviour over time. A current state in crowd behaviour is regarded as the result of previous interactions of individuals with their environment. Overall, developing a model of crowd behaviour involves an integrative and multi-level approach in which the role of the individual, situation-dependency and dynamics play a central role.

The model consists of a framework that includes both the environment and individuals. The environment can be filled with physical and social elements, in which this study includes relevant influence factors such as the density level (physical) or the amount of leaders (social) in a crowd. The environment reflects descriptions of a crowd on group level. The individuals on the other hand generate behaviour while being influenced by their external and internal world. This implies that whatever influence factor is incorporated into the model (either at group or individual level), it must explain the way by which this factor affects an individual. In this thesis individuals are considered human information processing units (i.e. cognitive systems). All influences go via the individual, which implies that in explaining group level patterns, an explanation should be sought by relating the group level to the (intra-) individual level.

An individual in a crowd is regarded as situated, which means that an individual is both *embodied* and *embedded*. Embodiment refers to the physical characteristics of having a body influencing human information processing. For instance, only what is perceived influences behaviour, thus something that happens behind a person that is not perceived will not affect their behaviour. To be embedded says something about the current external and internal setting that needs to be incorporated to reproduce situation-dependent behaviour. To regard an individual as a cognitive system includes being embodied, but also to have internal representations that allow an individual to interact with the world around him. The level at which behaviour is described allows for tracing *what* behaviour is chosen and *why*, given the internal state of that person at that time.

In addition to the contribution to theory, this thesis wishes to make a methodological contribution as well. Computer simulation supports understanding of crowd behaviour as it allows for limitless experimentation, only the theory limits the boundaries of exploration. Furthermore, it allows for exploring the dynamic aspect of crowd behaviour, which sets out an important point of view from which crowd behaviour is explained. Before simulation experiments can be run, a computational model is needed. By formalising CROSS into programming code (i.e. a computational model), crowd behaviour can be generated and thus explored. Every relation that is described in the conceptual model needs a computational structure (e.g. an algorithm), every concept a representation of a computational element (e.g. a variable or class). This step of computational modelling makes the theory more concrete and easier to communicate.

The computational form of CROSS is used to perform simulation experiments. In performing experiments the options are endless, however to be able to grasp and validate what happens it is important to start simple. This thesis describes two experiments: one that explores the role of density (a physical factor) and one that explores the role of leadership (a social factor). Both factors are of practical relevance as both play an important role in crowd behaviour. In addition, both density and leadership are potentially of influence in real life, which make them even more relevant for exploration.

1.3 Thesis map

This thesis describes the road to understanding crowd behaviour, see figure 1.2. Chapter 2 describes the crowd research area. Current crowd research forms a solid base to proceed from, but also formulates a need for a generic testable theory and for a method that allows for testing theories. This description of crowd research in chapter 2, is followed in chapter 3 by a description of the theoretical model of crowd behaviour CROSS developed for this study. Chapter 4 then deals with the use of simulation as a methodology to explore and test theories. The last part of the thesis focuses on the use of the CROSS model to gain understanding of crowd behaviour. First, a computational version of the CROSS model is described in Chapter 5, followed by the description of simulation experiments in chapter 6 and 7. In these experiments the role of density (chapter 6) and leadership (chapter 7) in crowds is explored. The thesis concludes with chapter 8 by reflecting about the contributions made to crowd research and future steps in understanding crowd behaviour.

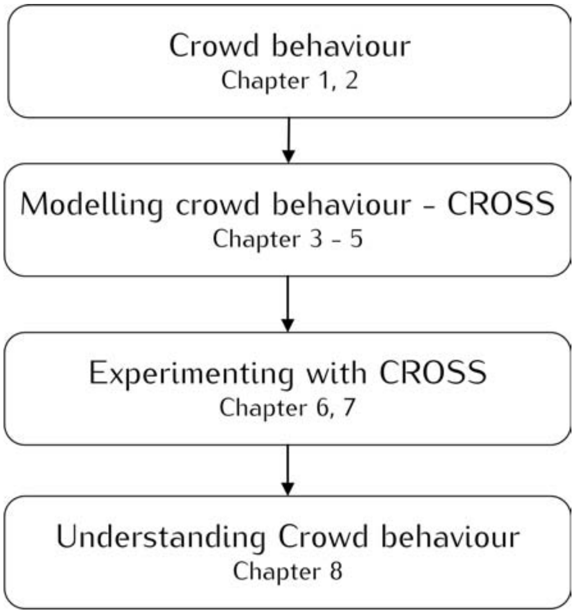

Figure 1.2: Thesis map visualisation

Chapter 2

Crowd Behaviour

The existing literature on crowd behaviour involves a variety of definitions, descriptions, views and explanations. Several of them will be addressed in this chapter to lay the groundwork for the definition, focus and aspects that are considered necessary to proceed in understanding crowd behaviour.

Crowd behaviour is the behaviour that is conducted by individuals who gather in a crowd. However, what is exactly meant when talking about crowds and their behaviour? In everyday life, the word crowd is used to indicate a range of situations that involve an assembly of persons. For example a crowd at a festival, or a crowd on the internet to buy tickets for a concert. Usually, the context in which the word 'crowd' is used indicates what type of group is meant in terms of size, duration, composition, motivation, cohesion and proximity of individuals.

The crowd example in chapter 1 of the beach festival illustrates this meaning through context. Crowd behaviour at the festival is for instance clearly different from crowd behaviour in the shopping street (see the boxes 1-3 examples in chapter 1). In the shopping street the crowd consists of identifiable small groups, each pursuing their unique shopping goals, but all of them have the goal to shop. At the festival different groups can be identified. J* belongs to several of these groups. A small group of companions with whom J* came to the festival. But also a larger group in which J* and others are dancing in front of the stage. The dancers share the way of fulfilling their goal to enjoy music, while the shoppers differ in behaviour to fulfil their goal as they are not all heading for the same shop. The differences between the crowds are hard to catch in a definition as they are situation and time dependent what kind of group is dealt with.

In the field of crowd research there is no consensus on the definition of a crowd. The definitions evolve around the concept of a gathering (Challenger, Clegg, & Robinson, 2009b) accompanied by a description of what binds the individuals in the crowd. To give some examples - *"A crowd is a temporary gathering of individuals who share a common focus of interest"* (Forsyth, 2006). For Reicher (2001) on the other hand, a crowd is only a crowd when *"individuals share a social identity"* (Reicher, 2001). Regardless of the differences in the core of these definitions, they all share the notion of a number of people in the same place at the same time, i.e. a gathering (Lofland, 1985). Most definitions include the concept of a psychological group by adding a binding between the individuals in a physical crowd, i.e. a social relationship (Forsyth, 2006, p. 4). Depending on the theorist this social relationship is defined as a shared commonality, such as fate, goal, social identity, interaction, structure, influence, interdependence (Forsyth, 2006; Brown, 2000).

In this thesis a definition of a crowd is needed that allows for studying crowd behaviour patterns and the dynamics of these patterns with as little assumptions as possible. The minimal description starts from a notion of a group. A group is defined here as *a set that holds at least two elements*, without any other characteristics being specified. In the context of a crowd a group can be any set of two or more individuals, for instance people that are behaving in the same way can be attributed as a group. To refer to a crowd gives more information about a group of individuals as a crowd involves the co-presence of individuals at a specific physical location. When crowds are addressed by researchers or media this usually involves the rise and change of a psychological group, similarly to the definitions that are used, addressed in previous paragraph. However, a crowd does not necessarily need to be a psychological crowd, moreover it is relevant to capture this process of being part of a psychological group to gain understanding of crowd behaviour. In this thesis the definition for a crowd therefore needs to be able to encapsulate a non-psychological group and thereby deviates from the notion of crowds used by most crowd researchers, as these definitions assume too much about the relationships between individuals, which are exactly the relationships that need to be able to change and emerge during time. To recapitulate, in this thesis a crowd is defined as:

A group of individuals at the same physical location at the same time.

Crowd behaviour during an event can be described in a variety of ways given this definition of a crowd. Take for example the beach festival, described in chapter 1. At the beach festival a lot of behaviours were shown: dancing, drinking, listening to music, the clash between a group of visitors and the police. The event can be described by referring to the behaviour on the site, the interactions and incidents, that occurred within the range of hours during the festival (e.g. the threats, the chase and the counting of the hostile group). But also the warning shots and the fatal shot of the police could be included. Another way to describe the incident at the beach festival, is to place it in a wider frame of violence at events. One could describe the rise of a new trend, for instance a trend of hard-core football fans misbehaving outside the football area. Such a description encapsulates a wider scope. The focus in this thesis specifically lies on the behaviour and interactions as opposed to a focus on trends for instance.

The object of understanding is related to the focus taken in describing crowd behaviour, e.g. on site or a wider scope, placed on a temporal and spatial frame. A simple representation of the resulting matrix is given in figure 2.1 where McPhail (1991) displays the levels on which crowds and social movements have been studied as collective phenomena. The horizontal axis represents the spatial frame, units of space from geographical to political locales (i.e. a geograpical site, national, global, communities). Down the vertical axis units of time are represented moving from (split) seconds to a description over years. This study restricts itself to crowd behaviour that occurs within minutes or hours at a specific physical site, to events in which short-term and direct influences on behaviour within the boundaries of the site take place.

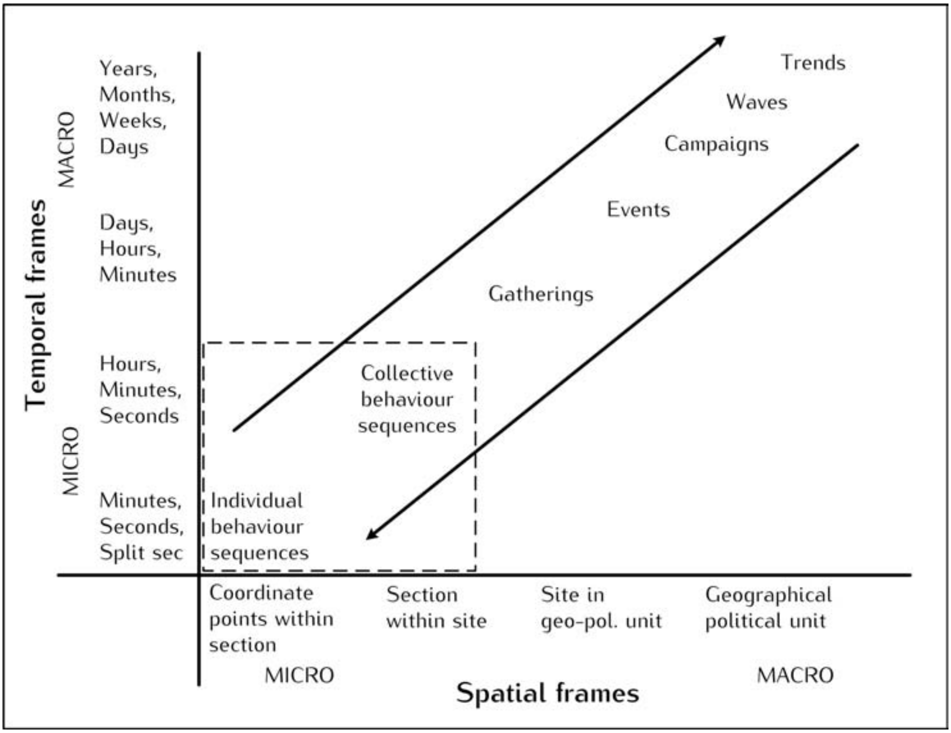

Figure 2.1: The spatial and temporal levels on which group and crowd behaviour can be studied. The focus of this study is indicated by the dotted box. (Source: McPhail (1991, p. 176))

The dotted box in figure 2.1 visualises this focus of short-term direct crowd behaviour. The boundaries resulting from this focus allow for the selection of relevant literature on crowd behaviour.

The following sections describe the evolution in crowd research from the beginnings to its modern foundation. The identification of several myths and insights shapes the new foundation of the field. It is important to be aware of the path this field has taken in the past, as it makes us aware of the intuitive pitfalls that this field is sensitive to. But most importantly, it gives direction in proceeding to gain a better understanding of crowd behaviour by incorporating the role of both group and (internal) individual processes.

2.1 Foundation of crowd behaviour

The field of crowd research is almost as dynamic as the phenomenon itself. Since the 18th century scientists try to explain crowd behaviour with a specific focus on riots. Since then it has gone through some extensive changes, from explanations without (social) context, to descriptions with an empirical base.

The field started off by producing crowd theories without a link to reality (Reicher, 2001), creating the so-called myths of *irrationality*, *emotionality*, *suggestibility*, *destructiveness*, *spontaneity*, *anonymity* and *uniformity*. All of these myths evolved around the view of a crowd as extraordinary, requiring a specific explanation. The following period evolved around falsifying these myths by numerous observational studies (Adang, 1998; McPhail, 1991; Couch, 1968; Berk, 1972a, 1972b, 1974b, 1974a). From then on the "extraordinary" was rejected and a new foundation for crowd research was formed.

2.1.1 The 7 myths of the traditional foundation

Crowd research was tainted with misconceptions for a long time. In traditional crowd research, crowd behaviour was regarded as completely different from any non-crowd situation[1]. At the base of these myths lie two types of theories: *transformation theories* and *predisposition* theories (McPhail, 1991).

The transformation theories are built on the idea of a *group mind*, coined by Le Bon (LeBon, 1895). Le Bon stated that every individual in a large gathering is transformed into a crowd member. The crowd puts them in the possession of a collective mind, which makes them feel, think, and act quite differently from a situation in which each individual would feel, think, and act, were he in a state of isolation (LeBon, 1895). This group mind theory had a huge impact, it was not only the first psychological theory on crowds, but it also coined crowds as extraordinary. This shaped the general view on crowds as it became a widely accepted explanation for crowd behaviour. The transformation of individuals into a crowd, in terms of the loss of self, formed the base for other theories, such as the still influential deindividuation theories (Festinger, Pepitone, & Newcomb, 1952; Reicher, 2001). These theories focused on describing the process where an individual deindividuates, the process in which people supposedly lose their sense of a socialised individual identity and engage in unsocialised, often antisocial behaviour (Hogg & Vaughan, 2008).

The second stream, the pre-disposition theories, actually explained the same process of showing similar behaviour in a crowd. However, instead of having a notion of a group mind that steers crowd behaviour, the steering force lies on the individual level. The similar innate drives that individuals in a crowd supposedly share, i.e. predispositions, give rise to similar crowd behaviour (Allport, 1924; Miller & Dollard, 1941). Typically, the power of control was transferred from a collective property (group mind) to a similar property for all individuals.

Even though current crowd research considers these theories as outdated, they still tend to pop-up implicitly in other theories, textbooks (Schweingruber & Wohlstein, 2005), or in popular communication about crowds. The myths represent intuitive pitfalls. It is therefore important to be aware of them. In the following, 7 myths are described, adopted from Schweingruber (2005) which is in its turn based on the identification made by McPhail (1991) and Couch (1968):

- Myth of Irrationality : the idea that individuals in a crowd lose rational thought
- Myth of Emotionality : the idea that individuals in a crowd become more emotional

[1] It needs to be noted that crowds were seen as an equivalent of riots.

- Myth of Suggestibility : the idea that individuals in a crowd are more likely to obey or imitate
- Myth of Destructiveness : the idea that individuals in a crowd are more likely to act violently
- Myth of Spontaneity : the idea that in a crowd violence occurs more suddenly
- Myth of Anonymity : the idea that individuals in a crowd feel more anonymous
- Myth of Uniformity/Unanimity : the idea that all individuals in a crowd act in the same way

Myth of Irrationality

The myth of irrationality conveys the misconception that people lose the ability to think rationally (Schweingruber & Wohlstein, 2005) when in a crowd. The notion of irrationality is often used when people are not behaving in what is seen as the most effective way to achieve a goal, like fleeing out of a building while not following the emergency exits. However, the effectiveness of behaviour is compared to an ideal way of acting. It thus depends on whoever defines the effective or ideal way how and when the label "irrational" is used.

The irrationality myth is a direct consequence of the traditional crowd theories, based on the group mind and predisposition theories. The control by either a group mind or shared predispositions describe a cognitive shut-down, hence irrationality.

Criticism. The fact is that people in crowds do not behave irrationally, i.e. do not encounter a cognitive shut-down. Actually, the available evidence supports the opposite: individuals behave rationally given the information they have and they pursue goals effectively (Couch, 1968; Adang, 1998). The example of the beach festival in chapter 1 serves as a good illustration of absence of irrationality. The persons who conducted violent behaviour were clearly not in this confrontation by accident - as they stated themselves their intention was to "go loose" (Wanders, 2009, p. 3). A police-officer even reported that a member of the ‘hard core football supporters’ warned him about a large group knowing about the absence of the riot police, so the police had better leave (Muller et al., 2009, p. 71). Another indication of the absence of irrationality is the count-down of the group rioters at the peak of confrontation while having the police surrounded.

These are just a few examples that show that people who seek the excitement will be present, while others will avoid it. In the case of the beach festival riot at least 99% of those who were present did NOT join the riot. But those who were actively involved did so deliberately. The hostile group at the beach festival pursued their goal to chase and beleague the withdrawing LEOs for some time. This is conscious, deliberate, and even strategic behaviour and as pointed out by Adang (1998): rioters make risk analyses based on the probability to get caught or hurt. In all, there is no good reason to consider the behaviour in a crowd to be irrational[2].

[2]However, the statements given by the LEOs shows that the irrationality myth still lives. LEOs stress that the behaviour of the violent group was irrational by stating that they "were undiscerning", not even for warningshots, or that the group was intoxicated of alcohol and drugs etc.

The absence of irrationality can also be found in non-rioting crowds. For example, the usually supposed irrational behaviour of a ‘panic’ in case of an emergency. People in an emergency are expected to randomly flee, or freeze (Burton, Kates, & White, 1993; Gross, 1990; T.Horlick-Jones & Jones, 1993; Purdom, 1990), which in reality appears to be far from the truth. In buildings people choose the route they know or when not familiar with the building their exit route is the way they entered the building. Although it might not be the most optimal route, this does not imply irrationality or randomness. The optimal route would be to follow the emergency-exit signs as this would be probably faster, shorter and safer. However, the route that a person chooses is the one he is completely sure of to be a successful exit-route, which is often the same route someone came in, which can be considered a risk assessment.

The myth of irrationality is not based on the reality of crowd behaviour, it is derived from biases and prejudices. It is one’s own frame of reference that causes them to assign the label of irrationality, to the behaviour of others. During the time that the myth originated, the crowd (the French working class) were seen as irrational because their ideas were not consistent with those of the ruling "authoritative" institutions (the bourgeoisie) (Couch, 1968; Reicher, 2001)

In this thesis the idea of irrationality is rejected. Individuals behave according to the information they have at hand (i.e. humans are information processing systems). Behaviour is chosen[3] based on the internal state of an individual, which is affected by the external world. In that sense all behaviour is optimal given the restrictions of a given situation in terms of time, information and physical ability.

Myth of Emotionality

The myth of emotionality conveys the idea that people in a crowd are governed by their emotions, relative to those who are not in a crowd. The underlying implication supposes that being more emotional implies irrationality.

Criticism. The fact that a crowd phenomenon, such as a riot (threat, danger, risk) or a festival (fun, adoration of an idol) incorporates a context that holds strong emotions does not in itself distinguish a crowd context from any other situation (Couch, 1968). Emotions are clearly present in other forms of social interaction as well, imagine the interactions between a husband and wife or between an employer and employee (Turner & Killian, 1987).

The insinuation that emotions cause irrational behaviour is not only false, but rather the opposite is true. Emotions and irrationality are mutually exclusive, as Schweingruber (2005) identifies, e.g. (Aminzade & McAdam, 2002; Goodwin, Jasper, & Polletta, 2001; Massey, 2002). Emotions actually seem to be the necessary component to be able to take rational or logical decisions (Damasio, 1994).

This myth is a typical example of placing everything that concerns a crowd under the label of ‘extraordinary’. Le Bon provides a solid example of this by claiming *“Isolated, he may be a cultivated individual; in a crowd is a barbarian, that is a creature acting by instinct..”* (LeBon, 1895, p. 8). In that sense, it is just a small step from the idea of primitive beings more emotional as a negative to irrationality. The identification of emotionality as a myth regards an individual not to be any different inside or

[3] To choose a behaviour does not imply a conscious act.

outside a crowd. It is the context that differs, but this does not change anything about the cognitive processes inside individuals.

Myth of Suggestibility

The myth of suggestibility claims that especially individuals in a crowd are likely to obey or imitate. Park (1904) coined it: suggestibility. He took over the group mind concept of Le Bon(1895) and focused on the process of losing one's individual consciousness and in particular one's self-consciousness. Suggestibility was described as the phenomenon in which feelings and thoughts of all members move into the same direction. The suggestibility increases not due to physical proximity, but through infection of thoughts and feelings (McPhail, 1991, p. 5-9).

The idea of being infected is adopted also in the *contagion theories* (Forsyth, 2006; Brown, 2000; Baron & Kerr, 2003). The contagion theories describe group behaviour as a disease spreading via individuals infecting each other.

Criticism. There is no evidence that supports the idea that people in a crowd are more obedient than people in other settings. However, if this were true, the crowd would pose no problem for authorities, as the crowd would listen to authorities (Couch, 1968, p. 312). Or to look at it differently, the police or other groups appear to be immune, how does that come about? The concept of suggestibility is completely built on the group mind view on crowd behaviour. The concept of a group mind has been refuted by modern crowd research, making any theoretical refinement derived from the group mind view just as false.

Behaviour in a crowd is too complex to describe it in terms of suggestibility or contagion. The idea implies that all people act in the same way in a crowd, which is not what reality shows (see also the myth of uniformity below). A broad array of behaviours is displayed, that changes over time. To explain patterns of behaviour in which some people seem to imitate or act obediently, a richer description is needed than the adoption of thoughts of feelings. The behaviour choice is moved from the individual to the group mind, however how does this group mind make up his mind? The situational and especially the social context needs to be refined in explaining observed obedience or imitation, as they are relevant in the decision making of humans.

Myth of Destructiveness

The myth of destructiveness claims that people in crowds are more likely to act violently towards other people or property. Crowds are notorious for rioting, i.e. crowds in which some people display aggressive or violent behaviour. Riots can have a big impact on society. People can get hurt or die, feelings of safety are threatened, especially when a specific group is targeted (e.g. a minority in race riots or the bourgeois during the French revolution). This can also occur when a situation is violent that is supposed to be cheerful, such as the football riots or a festival like the one described in chapter 1.

Criticism. Crowds being destructive is an assumption that is easily refuted. The counter evidence found by simply observing crowd behaviour in reality as the occurrence of violence in crowds is rare compared to all crowd events (Eisinger, 1973; McPhail, 1994; Adang, 1998). Violence is not more likely in crowds than in any other situation and violence is not restricted to crowds (Couch, 1968).

The reason for individuals to act violent or aggressively is linked to a current situation, not to the crowd setting itself. It is important to address the relevant context in understanding behaviour and to avoid assumptions like the crowd-aggression link.

Myth of Spontaneity

The myth of spontaneity accounts for the perceived suddenness of violence that occurs in seemingly peaceful crowds. The myth is actually a combination of the destructiveness, and irrationality myths. Spontaneity is connected to violence and in this way the destructive myth is embedded. The perceived suddenness implies a factor of unexpectancy relating to non-normative or undesired behaviour, hence dis-functional rationality.

Criticism. As discussed in the criticism of the irrationality myth, behaviour is well chosen. It serves the goal an individual is pursuing. The point is that not all behaviour has an observable cause. Spontaneity indicates that something is unexpected for an outsider implying that either there was no external cause for the behaviour at hand, or the cause was too subtle or simply was not noticed.

Behaviour, either externally or internally influenced, is selected based on the internal state of a person. The internal state is, of course, affected by the external world, however it does not necessarily need to be the most dominant influence on behaviour. Take for example J*'s behaviour at the beach festival standing in front of the stage. J* is dancing and singing along quite fanatically during a performance for some time, but then suddenly J* walks away from the stage. This sudden change of behaviour is quite unexpected or spontaneous given the recent series of behaviour. However, the fact J* needs to go to the toilet quite urgently makes it less spontaneous. An internal trigger was the dominant factor at that time, which made J* change his behaviour sequence. What is spontaneous or unexpected lies in the eyes of the observer. Taking relevant external and internal context into account, changes the concept of spontaneous behaviour in crowds.

Myth of Anonymity

The myth of anonymity holds that individuals feel anonymous when they are in a crowd. Consequently, the behaviour individuals display is less inhibited and increased anti-normative (Diener, 1980; Zimbardo, 1969). Anonymity is considered a crucial factor in the transformation of individuals into a crowd, i.e. deindividuation (Festinger et al., 1952). Deindividuation is the process by which people lose their sense of a socialised individual identity and engage in unsocialised, and often antisocial behaviour (Hogg & Vaughan, 2008, p. 421). This link between anonymity and deindividuation implies that being in a crowd provides individuals with a cloak of anonymity that diffuses personal responsibility for the consequence of their actions (Zimbardo, 1969; Cannavale, Scarr, & Pepitone, 1970; Diener, 1977, 1980; Prentice-Dunn & Rogers, 1989).

Criticism. No strong support can be found for the anonymity myth, actually the opposite effect is encountered. The subjects in the experiments that formed the basis for the deindividuation theory were in fact more likely to act according to the norms when they were supposedly 'deindividuated' (Postmes, Spears, & Lea, 1998) instead of the other way around. Even the pioneering researchers of the deindividuation theory found contradicting results (Diener, 1976; Zimbardo, 1969). In addition, observational studies show that people in a crowd assemble with friends or family (Aveni, 1977; McPhail, 1991, 1994) which leaves them far from being anonymous. Actually, they are more likely to act collectively than anonymous individuals are (Neal, 1994). The fact that individuals avoid to be recognised by the LEO's when performing a punishable act is part of risk-reducing behaviour. On the other hand being seen by your friends while doing so, can be status-enhancing. Thus anonymity begs the question: "Anonymous to whom?".

People do not lose there sense of self in a group. The behaviour that is displayed is part of human decision making in achieving the goals a person strive's for, e.g. avoiding punishment or bolstering status. The dominant role of the social context, e.g. friends, is blurred by the bias of the observer. Behaviour is labelled as irrational because the observers norms did not apply to this situation, however the norms that matter are those that are relevant for the person in the context. Instead of comparing a behaviour with the norms applicable for a given setting, the observers compares a behaviour with their own norms. The debunking of this myth emphasises the role of the social context in crowd. In addition, it reaffirms the importance of integrating the individual level to understand behaviour.

Myth of Uniformity

The myth of uniformity claims that every individual in a crowd is continuously performing exactly the same behaviour (McPhail, 1991, p. 71). Even though both the transformation as well as the pre-disposition theories differ in their approach, both theories assumed uniformity in crowd behaviour and attempted to explain it (McPhail, 1991, p. 71).

Criticism. This was one of the first myths to be falsified by simply observing real crowd phenomena. *“..it laid the groundwork for a fundamental breakthrough in describing and explaining crowds and collective behaviour”* (McPhail, 1991, p. 89). Turner & Killian (1987) coined this myth as the *’illusion of uniformity’.* Crowd behaviour is a heterogeneous and changeable phenomenon that in specific moments, people may engage in collective action (e.g. applauding, a Mexican wave, or praying). However, in most circumstances the behaviour shown is quite diverse. This myth illustrates the effect of mixing up the way we talk about crowds (i.e. the most striking behaviour), and what actually happens in a crowd.

In chapter 1 the example provided indicates that a riot occurred during the beach festival. Some people engaged in aggressive or violent behaviour, in fact just 200-300 of the approximately 25.000 visitors did so. Similar accounts are given in the systematic observational field study of crowd events by Adang (1998, 2010). These studies indicate that of the events in which violence occurred, always less than 10% (usually no more than 1%) of the crowd was actually involved in violent behaviour (Adang, 1998; Schreiber & Adang, 2008a). The other 90% (to 99%) made other choices, e.g. passively watching, encouraging the rioters by cheering, or literally walking along with the rioters (Adang, 1998; Schreiber & Adang, 2008b).

Acknowledging uniformity as a myth changed the object of explanation. It forces to make explicit what it is subject of study and furthermore to take the dynamics and heterogeneity of the individuals in a crowd into account. In this thesis, crowds are studied by focusing on the group level patterns of the behaviour that emerges. To be more specific, these patterns are clusters of individuals who (temporarily) behave in a similar way, or to use McPhail's definition: *collective-behaviour-in-common*, i.e. *"when two or more persons engage in the same behaviour at the same time"* (McPhail, 1991, p. 44), with the additional constraint that they are in each others physical vicinity, i.e. form a cluster. Furthermore, the heterogeneity of the crowd is stressed. Heterogeneity refers to the differences within a crowd, either in terms of behaviour, or individual distribution (sex, age, number of friends present, etc). Every individual has their own unique local surrounding, but also a unique internal setting that affects interpretation of what is perceived and this plays an important role in the behaviour a person will or will not exhibit.

2.1.2 A Reflection on the myths

The developments in crowd research are valuable as they convey a few important lessons that will influence future research: crowd behaviour is not a unique state of behaving, it is important to avoid intuitive pitfalls, there is a need for scientific rigour in studying crowds and a multi-disciplinary, integrative approach is crucial.

First, crowd behaviour is not extraordinary. To regard crowd behaviour as non-extraordinary, theories that describe human behaviour can now be used. The rejection of the existence of a group mind stressed the individual level as the level of behaviour generation. The focus on individuals in a crowd changes the way behaviour is explained. The individuals are the ones that are affected. Individuals are necessarily part of an explanation of crowd behaviour patterns, such as collective action. This forces a shift in focus towards individual level behaviour dynamics with behaviour patterns at group level.

The second lesson teaches us to avoid pitfalls, such as applying too narrow a focus, or neglecting the role of the context. Crowd phenomena encompass a wide range of events and behaviour. Due to the tendency to readily focus on the perceived extreme or striking elements (e.g. riots and evacuations), and regard them as representative of crowd behaviour in general, a too simplistic explanation is applied to explain the whole range of crowd events. In addition to a limited focus on extreme crowd settings, the explanations provided have also been tainted by a tendency to overestimate the influence of personality, but neglecting situational influences (fundamental attribution error (Fiske & Taylor, 1991)).

The third lesson teaches us that a suitable method is needed to gain more understanding of crowd behaviour. Crowd research especially needs strictness in the use of a scientific methods to avoid a continuation of misconceptions. *"Science is a conversation between rigour and imagination."* (Abbott, 2003, p. 1). To use Abbott's metaphors: the interchange is key between method and intuition, traditional crowd theory was having a monologue in imagination. Hence the resulting myths that shaped a view on crowds for years without empirical referent.

The fourth and last lesson involves the need for clarity. Crowd research and practice is full of concepts that are used in a variety of ways as it spans over disciplines. Take for example the fact that there is not one general agreed definition of crowds (Challenger et al., 2009b). To be able to work in a multi-disciplinary and integrative way, it is necessary to be clear about the meaning of concepts to be able to discuss and interpret each other's work without being held back by ambiguity. To support communication and integration, clarity is needed in the concepts that are used, e.g. by being explicit about the level(s) of description and definitions that are used.

2.1.3 The modern foundation of crowd behaviour

The iterative process of theorising, criticising, detecting misconceptions, and gathering empirical data over the past three decades have made specific what crowds are not. But the developments have also resulted in new descriptions of crowd phenomena, and more clarity with regard to definitions and levels of analysis. Based on this knowledge three important insights are formulated that represent the modern view on crowd behaviour in this thesis:

- Crowd behaviour is generated by individuals
- Crowd behaviour is context dependent
- Crowd behaviour is dynamic

Crowd behaviour is generated by individuals

Behaviour in a crowd is generated by the individuals in it. To understand crowd behaviour, the group level needs to be related to the individual level. Rejecting the idea of a crowd mind emphasizes the focus on the individual in a crowd, instead of on the crowd as a whole. This implies that the behavioural patterns that arise at a group level cannot be explained solely in terms of group level descriptions; as the behaviour arises on the individual level.

This insight leads to an individual-driven perspective. To describe an individual in a crowd context relevant theories and factors need to be incorporated that describe individual behaviour and individual information processing. Each individual responds and is affected in its own unique way, resulting in a heterogeneous crowd.

Crowd behaviour is context dependent

Every situation and individual is unique, and so is the behaviour that is generated by an individual in a certain situation. Behaviour occur in a context and (perceptions of) external stimuli (in interaction with internal factors) affect individual choices in any given context. For example, the crowd at a beach party may behave differently depending on the weather, the music being played, the presence of police, or the what happened at a previous festival. It is important to incorporate the relevant situational factors to understand the behaviour patterns at any given moment. Both the physical and social context are important in crowd behaviour, and it should be stressed that crowd behaviour is a social phenomenon. The social context is part of situation dependency in general, however it is stressed here as it is an important source of influence on behaviour. The traditional "extraordinary" view on crowds which developed from the concept of group mind, resulted in explanations which separate the crowds from their social context (Reicher, 2001). In a crowd individuals are surrounded by acquaintances, friends or family (Aveni, 1977; McPhail, 1991, 1994). This implies that individuals in a crowd are sensitive to their co-crowd members. Behaviour in a crowd is not a simple social reflex, it is an active product of the interaction of an individual with its social environment (Couch, 1968). In understanding crowd behaviour the social setting is part of the crowd context that needs to be taken into account.

Crowd behaviour is dynamic

Behaviour in a crowd continuously changes. These dynamics are the consequence of the role of situational influences over time. In that sense, crowd behaviour is a complex system with a multitude of potentially interconnected factors that play a role. The interactions between the individuals give rise to the emerging behaviour patterns in a crowd. The behavioural patterns themselves also affect individuals, and thus, the behaviour they display, a case of downward causation.

A snapshot of a crowd freezes a singular moment and does not capture the events leading to this moment. Every time-step represents a unique picture. It is important to incorporate the underlying processes or preceding events to be able to understand how and why a certain behaviour pattern arises. The changes over time (i.e. the dynamics) are not just a typical characteristic of crowd phenomena: they are an essential element to take into account when aiming to understand behavioural patterns in a crowd.

2.2 Existing models based on the modern foundation

Below the current models that are based on the modern foundation will be dealt with. They all assume individuals to behave and they all incorporate the role of the (social) context and the dynamic nature of the phenomenon. All these models focus on describing disorder.

2.2.1 Flashpoint model

The flashpoint model (Waddington, Jones, & Critcher, 1989) explains the circumstances under which public disorder is likely to break out or fails to "ignite" with use of a general framework (Waddington, 2007). The general framework integrates relevant factors by attributing them to a level of analysis and explains from each level how likely disorder is. The model incorporates six interdependent levels of analyses: structural, political/ideological, cultural, contextual, situational and interactional. Each level describes a relation between disorder and relevant factors. The factors range from global contextual factors (macro) to face-to-face interaction (micro) factors. For instance macro factors defined on the structural level, such as material inequality is related to collective grievances or resentment in society. In terms of the interactional level, the direct interactions between groups are taken into account to explain potential disorder. The "flashpoints" represent incidents that may spark off disorder, each level functions as an situational indicator whether an incident may function as a flashpoint.

The model has been used to describe a variety of public order events. It is flexible in dealing with different types of disorder, losing situational detail (Waddington, 2007). Even though the authors consider their model as an explanatory framework, the model has been subject to substantial criticism on this point (Schreiber, 2010). The main point of criticism is directed to the explanations that do not cover the mobilisation phase of disorder; the self organisation of crowds and police; and the riots without an external trigger or a delayed response to an external trigger (Otten, Boin, & van der Torre, 2001; Waddington, 2007).

In line with modern insights, the model goes through great lengths to incorporate the role of situation dependency within the general framework. By separating levels of analyses multiple factors are integrated side by side. The levels include the role of social context. However, both the role of individuals and the dynamic aspects are not incorporated. The interactional level focuses on group interaction as opposed to interaction between individuals (belonging to a group). With regard to the dynamic element, the sequence of flashpoints or a delayed response cannot be explained using the model. The main contributions of the flashpoints model are the effective way of dealing with a complex phenomenon by distinguishing between different levels of analysis, the situation-dependency and the approach to provide a general explanation for disorder.

2.2.2 ESIM model

The Elaborated Social Identity Model (ESIM) (Reicher, 1996, 1997, 2001; Drury & Reicher, 1999; Stott & Drury, 1999; Stott & Reicher, 1998) is a social psychological explanation of crowd behaviour that incorporates group interactions, e.g. the police versus the crowd. ESIM describes crowd behaviour based on the way people perceive themselves as group members, in terms of their social identity (Tajfel, 1981) and self-categorisation (Turner & Killian, 1987; Turner, Oakes, Haslam, & McGarty, 1994)[4]. These processes of social identity and self-categorisation explain how a person that feels like a football supporter, will act as a football supporter. To specify this, when categorising oneself in a certain membership type, the (perceived) norms and thoughts of what is appropriate, given a the prototypical group member, shapes the behaviour that is shown.

According to the model, collective action, i.e. action in common, can only take place when members share (or perceive themselves to share) a common social identity. The perception of group characteristics and norms changes over time this is regarded as social change (Reicher, 1996; Drury. & Reicher, 2000).

The ESIM model is used to explain public (dis)order. Crowd behaviour is reflected by the social identity of its members in a variety of contexts, e.g. football (Stott & Reicher, 1998), student demonstrations (Reicher, 1996), political demonstrations (Drury & Reicher, 1999) and environmental protests (Drury & Reicher, 2005) in England and Scotland. In addition to the strong focus on the social context, the dynamic component of a crowd event is also incorporated in the model by stressing that crowd events can lead to social change, via re-categorisation of social identity. Disorder is described in terms of asymmetric relationships between groups, implying that differing perceptions of the same social context are held by the two groups, which can lead to an increased negative tension between the groups (e.g. us versus them). This can for instance be caused by an intervention by the police that is regarded as inappropriate

[4] Self-categorisation is the process that describes the way we categorise ourselves as member of a particular group.

by the public. When a relationship between groups (e.g. police and demonstrators) becomes asymmetric (Stott & Drury, 2000) a re-categorisation of group membership and the appropriate norms can, for instance, lead to a situation in which violence is regarded as appropriate.

The ESIM model has made a valuable contribution in explaining public disorder (Stott, Adang, Livingstone, & Schreiber, 2007, 2008). In a study by Schreiber (2010) the ESIM model was applied to a (non-Britisch) cultural context. This study confirmed the explanatory value for most instances of crowd violence. Schreiber points out that all but the cases of spontaneous violence (i.e. violence without a clear external trigger), could be explained in terms of group relations. Explaining for the cases of 'spontaneous violence' would be a potential next step in refining the existing model.

The model is one of the best explanations currently available on processes underlying crowd behaviour. It has a strong focus on disorder and the social context. Although it confirms the importance of the social context, the role of other situational factors are not taken into account as much. These might be relevant when the behaviour under explanation is different from disorder. In addition, the focus lies on the interaction between groups, where the in-group interactions could also be relevant. Similar to the flashpoint model, the individual level is not really included.

2.2.3 The initiation-escalation model of collective violence

The initiation-escalation model of Adang(2010, 1998, 1991, 1990) maps the initiation of violence based on a systematic observation study of protest and football events. The observational studies are part of the stream that debunked the myths, and thus, part of the formation of the modern foundation. In this model the observation studies form the ingredients for the explanation of the initiation and escalation of collective violence. First, by describing the behaviour and events involving initiation and escalation. Second, by analysing the phenomenon from an interaction perspective, making explicit that violence cannot be understood without looking at the interaction of at least two parties that are always involved.

Given that crowd behaviour is a difficult domain to perform empirical research, Adang (2010, 1998) shows that it is possible to conduct meaningful structured observations. These observations provided evidence for the absence of irrationality in the behaviour individuals show. Rather, people behave in a way that is meaningful for themselves. No uniformity is observable, i.e. not everybody acts in exactly the same way. Individuals differ, their local situation differs and thus make individual choices based on what they know, resulting in heterogeneous crowd behaviour. Adang refers to (van der Valk & Linckens, 1988; Harrington, 1968; van den Brug, 1986) to argue that being in a crowd does not make a person more violent than outside the crowd.

The observations describe what really happens in a crowd. This did not only help to debunk myths, it also provided a description of the initiation of violence and escalation. A distinction is made between two ways in which collective violence is initiated[5]: violence that has a clear identifiable trigger (response to the external situation, i.e. reactive) on the one hand and violence that does not have this trigger, which makes it seem spontaneous. The last type of violence, without a clear trigger, was almost exclusively performed by adolescent or young adult males.

[5]Collective violence implies multiple people (> 2) in a crowd that are engaged in violent behaviour.

The escalation of collective violence, i.e. more people getting involved, is explained by (a combination of) two different mechanisms: *risk perception* and the existence of the *us versus them* perception (antagonism) between groups. Risk perception involves a mechanism that describes potential escalation based on the risks/opportunity that is perceived. Especially young adult males have the tendency to take more risks and to be violent, an expression of 'the young male syndrome' (Wilson & Daly, 1985). These young males actively seek out opportunities to confront rival groups and they reduce (their perception of) risks by being together and acting with their mates.

The other mechanism, the 'us versus them' antagonism, reflects group relations. The 'us versus them' mechanism involves the perception of one's own group (the in-group) relative to another group (the out-group). For example, when going to a sport event different supporter groups are celebrating the fact that it was an exciting match results in a 'we - we' situation. Another setting could be that different supporter groups are acting provocatively towards each other and an 'us versus them' setting is created. Both situations create different group dynamics, which determine the way behaviour is interpreted and responded to. These group dynamics are explained in terms of group relations and social identity changes in a escalating or de-escalating way, corresponding with the ESIM model.

The model stresses a contextual approach in understanding escalation and led to several practical messages, specifically to avoid frictions between groups. In contrast to most models, this model stays close to the real phenomenon. This makes it a strong model as it covers both violence with and without a trigger.

2.2.4 A reflection

The developments in crowd research have caused a huge shift in theorising, but also had practical consequences. Current models take the stance that crowds are social phenomena, they explain public (dis)order in that sense. The awareness of the role of context, of the dynamics involved, and of social mechanisms appeared to be successful. The research has its impact on policing, for instance, the use of individual targeted interventions as opposed to group interventions, which contributes to a 'we - we' relation between LEO's and the public. The practical impact is also reflected in the way the research done as it is conducted in collaboration with police and police research institutes (Schreiber, 2010). This win-win situation is a source of validation for the existing models and has led to decreased violence around matches throughout Europe.

To reflect over the current models a few things can be noticed. The models share a specific focus on disorder and share an type of explanation of disorder in which the social context is most dominant. The absence of testable theories that generate systematic knowledge of crowd behaviour may also be noticed.

Concerning the specific focus of modern crowd research, most work concerns public disorder and lies in the domain of football and protests. In this thesis it is regarded as crucial to gain a general understanding of underlying processes of group dynamics, not only of specific outcomes like violence or disorder. Even with a focus on violence, the processes leading up to disorder should be included to achieve a more complete understanding. The group processes that underlie violence are assumed to underlie any form of behaviour in a crowd including grabbing a beer with friends.

The insight that crowds are social phenomena is emphasised by the explanatory power current models have. However, crowd behaviour is not solely influenced by the social context. Individuals in a crowd are situated in a physical world that affect behaviour, for instance, when moving more slowly to cross a street when it is crowded. But also the role of the internal world of an individual plays a crucial role in behaving. The model of Adang already indicates that some indices of violence are not externally visible, they are internally triggered (i.e. the lower risk perception of young men). Furthermore, given an external factor, the way an individual is affected can differ from one person to the other. The inclusion of the internal world of an individual will result in more details about why a behaviour is chosen at a given moment in time.

The role of both the external and internal world defines a situation for an individual. The insight of situation dependency thus involves both the physical and social context, as well as the internal state of an individual. For a broad and complex field, such as crowd behaviour where a multitude of factors are interconnected (e.g. individual, group, interaction, social, physical), it is impossible to understand what is going on without crossing the borders of multiple scientific fields. To say it differently: one should act as if there are no borders, just options what to include or exclude.

Although the modern generation of models delivers an empirically based description of crowd behaviour and provides a socio-psychological explanation for disorder, most of the components of the models are not directly testable. To proceed in validating explanations, the field of crowd research is severely limited. It is practically impossible to perform experiments and test a theory or explanation. Behaviour in crowds is not only dynamic, the multitude of factors that play a role and are interconnected are hard to control for. Performing experiments on crowds would result in data that are unreliable or hard to validate. Importantly, it would lead to a situation with many ethical concerns, in which the safety of subjects cannot be guaranteed.

2.3 Conclusion

The overview of the literature shows how for a long time crowds and the behaviour displayed in crowds were regarded as extraordinary, requiring special explanations. Current crowd research has done away with many myths and unfounded speculations and brought crowd research back into the realm of the ordinary. The last two decades of empirical observational studies have shown that behaviour in crowds is not irrational, emotional, suggestible, destructive, spontaneous, anonymous or uniform and that the same types of rules apply within crowds that govern behaviour outside of crowd situations. Several insights are especially crucial for an understanding of crowd behaviour. First, when a crowd gathers at a physical location whatever happens and whatever patterns become visible is generated by the individuals present. Second, behaviour is situation dependent, meaning that the behaviour displayed at any point in time is dependent on the current context and internal state of the individuals concerned. Context includes the social context, which is regarded as an important source of influence in crowds. Third, crowd behaviour is a dynamic phenomenon, and this dynamic aspect cannot be overlooked when trying to understand behaviour at a certain point in time. Although the current models in crowd research, based on these insights, have made a great contribution to improve crowd management, they have their limitations: they focus on explaining disorder, usually restrict themselves to a socio-psychological perspective and, most importantly, they are limited in their ability to generate testable theories.

The limitations indicate that a broad approach in terms of scope and focus is needed to increase understanding of crowd behaviour in general. Therefore, it is necessary to have a broader look than a specific behaviour such as violence. The broadness need not apply only to the focus on behaviour in general, it is also meant to apply to situation dependency. The modern models stress the role of the social context by using a socio-psychological approach, this thesis advocates for the incorporation of the external context as well as the internal state of individuals. The external context includes both the physical and social aspects of the environment. Such an approach necessitates input from multiple disciplines to account for the role of physical and social factors on behaviour. Concerning the internal state an individual is regarded as a cognitive system. This makes it necessary to include aspects of human information processing and decision making into any explanation. An integration of relevant knowledge from both social and cognitive sciences is therefore required.

The insight that individuals in a crowd generate behaviour as opposed to the group (e.g. group mind) is the core of modern theories. However, this insight is not sufficiently reflected in the role individuals have in these theories. This thesis aims to restore the individual to its rightful place: the need for a multi-level study is stressed and the role of the individual is given the attention and descriptive richness that is needed to be able to understand crowd behaviour patterns.

2.3.1 Multi-level approach

Crowd behaviour is the behaviour of individuals in a crowd. It is a group level description of what a group is doing. Usually the most striking behaviour is used to describe crowd behaviour, such as aggressive behaviour or clusters of similar behaviour. It is important to realise that this description is an ascription. Groups and thus crowds are (literally) not behaving, the individuals in it behave, which is actually one of the recent perspectives in crowd research (see section 2.1.3).

Here the choice is made to explicitly talk about behaviour of individuals that belong to a group, not about behaviour performed by the whole crowd, unless every single individual performs it, e.g. as in an applause or line-dance. On the other hand, terms such as coordination, cohesion, synchronicity are used to describe an aggregate of group behaviour, or a state that can only be detected at the group level. In describing these kinds of group attributes words that imply a crowd as an individual unit are avoided as they tend to assign the human properties to a group.

As pointed out in the reflection of the myths (see section 2.1.2) there is a tendency to have false intuitions about what human crowd behaviour is. Consequently, ambiguity in concepts and theories may arise. For means of clarity as well as to better deal with the multitude of factors, a clear separation of levels and awareness of the level at which one is operating is crucial. In this study three levels are distinguished, the inter-individual (group), the individual (behavioural) and the intra-individual (cognitive) level.

The inter-individual - group level is the level at which patterns of crowd behaviour are observed. The patterns are the emergent[6] products or an aggregate description of a set of individuals as a whole.

The individual - behavioural level is the level at which behaviour of individuals arises and is observed. Behaviour is the external outcome of the internal decision making of an individual, affected by its internal and external state.

The intra-individual - cognitive level concerns the internal world of an individual. Both the bodily and mental state of an individual interact with the external world via perception (external affects internal) and behaviour (internal effects external).

The distinction between the levels is also necessary to gain understanding of crowd behaviour dynamics. On a group level, behaviour patterns arise that originate from the behaviour of the individuals composing a group. This emergent product can only be understood by relating the individual level with the group level. The same can be noted the other way around, behaviour might arise from the individual level, but is influenced by the other levels too. Take for example the role of downward causation, i.e. group level patterns such as being part of a culture, group, or just observing an out-group, affects the behaviour of an individual. Behaviour cannot be understood without distinguishing between the different levels of description and their mutual relations. Throughout this thesis these levels will be referred to as the group, individual and cognitive level.

2.3.2 Individual as cognitive system

One of the major insights of modern crowd theory is that crowd behaviour emerges from individual behaviour, which means that individuals behave. A group does not behave, but an individual can find himself in a group context that has a specific influence on the behaviour the individual displays. Traditional crowd theories drove out cognition from the individuals in a crowd, as Le Bon literally talks about: "..disappearance of brain activity.." (LeBon, 1895, p 1.). The modern foundation disregards this view of 'absence of cognitive activity'. However, current explanations do not incorporate the role of cognition, i.e. the way information is processed and behaviour is selected given a current internal state of an individual.

Observable behaviour in itself will not explain crowd behaviour patterns, as the behaviour on the individual level cannot be explained in itself either. To use J* once more as an example: at a certain point he is walking towards the bar. From the outside it is clear that he is walking and heading towards the bar, however it is not possible to say *why* he is moving towards the bar. Is he thirsty? He might as well just be joining his thirsty friend for social reasons.

To understand why and how behaviour and behaviour patterns arise a description of the internal world of an individual needs to be included. This thesis will do just that and trace how an individual gets affected by his current situation (externally and internally).

[6] In emergent phenomena, patterns are typically visible on group level that are not predictable from the individual level components. The complex interplay of the individuals gives rise to these patterns. The rise of new properties on group level, i.e. the behaviour clusters that cannot be explained from the individual level processes that cause them is called emergence (Humphreys, 2006).

Given the list of requirements identified in this chapter a general, integrative, multi-disciplinary approach that will describe individual behaviour from a cognitive system perspective a model is developed. As part of the approach in this thesis to provide for both needs of theory and methodology (simulation), the following chapter will describe crowd behaviour in which individuals are situated represented in the CROSS model. In this model, not only the role of the social context is acknowledged, but also the importance of the internal and external context of an individual is stressed (i.e. situatedness).

Chapter 3

CROSS - A Theoretical Crowd Model

The main topic of this thesis is behaviour patterns observable in a crowd. The understanding of the underlying mechanisms that give rise to the formation and changes of behaviour patterns are assumed to provide a deeper understanding of crowd behaviour. In chapter 1 some typical behaviour patterns were already addressed: *arcs*, *rings*, *lanes*, *companion-clusters*, see figure 1.1. J* was part of an arc in front of the stage, part of a lane while moving to the bar, and while doing all this he stayed in the vicinity of his friends. It is important to realize that crowd behaviour patterns are not restricted to detectable regularities in movement only. People who are acting in a similar way, like dancing or fighting, form a behaviour pattern as well. In this way subgroups in a crowd form, change and dissolve, i.e. the subgroups are dynamic. The formation and changes of such dynamic subgroups took place during the festival from the example given in chapter 1. People danced, laughed, sang, talked, drank, but there was also violence and a conflict between a group of 200-300 persons and the LEOs. All of these dynamic subgroups can be identified on the basis of the behaviour they exhibit.

To model the dynamic interplay of behaviour patterns the CROSS[1] model was developed. The CROSS model describes crowd behaviour using a multi-level approach where *individuals*, *context* and *interaction* play a crucial role. This description incorporates the view of the modern foundation of the crowd research, and it adds to it by including knowledge of human information processing, i.e. cognition. The rich description of an individual's internal world allows to understand *why* certain behaviour is chosen and helps to understand *how* behaviour patterns emerge at a group level. In this thesis, the particular focus lies on identifying general principles of crowd behaviour, rather than specific situations, e.g. riots or emergencies.

However, human behaviour cannot be described without incorporating the con-

[1]CROSS stands for a model of crowd behaviour that simulates situated individuals. The two foci are: 1) theory and 2) methodology. Symbolically, CROSS also stands for the boundaries of the scientific disciplines that are being crossed. In addition, a cross, or an x, is also a variable representing the variability of each individual. So even when behaviour is caught in a rule (i.e. formula) the outcome will differ based on the value of x.

text, even when the focus is on a generic understanding of crowd behaviour. It is the context that specifies the details that concretise the behaviour shown. In addition, it makes the model testable in relation to reality. In this thesis, a festival scenario is chosen to develop the model. A festival represents a dynamic gathering of individuals and a variety of attractions points (e.g. the stage, the bar, the toilet, other people). It is a relatively simple scenario (e.g. the area is restricted and the range of behaviour shown is limited), but sufficiently rich for the study at hand. In addition, there are many empirical descriptions of festival situations, e.g. (Kemp, Hill, & Upton, 2004; Muller et al., 2009), which allows for a scenario that is close to reality.

The CROSS model represents crowd behaviour by describing as well as relating three levels of description: the group level (inter-individual), the individual level and the cognitive level (intra-individual). These levels are visualised in figure 3.1. The group level, figure 3.1a, represents an overview of a crowd, where a physical and social environment can be identified in the form of a stage and other individuals, both festival public and police. Figure 3.1b, zooms in on individuals constituting a crowd and shows how an individual is affected given the current context. These are local influences. Figure 3.1c, displays the internal world of an individual, the level at which influence actually takes place. This multi-level approach allows for an increased understanding of behaviour patterns in a crowd (i.e. a phenomenon at group level) that are generated at the individual level. Behaviour in itself does not inform *why* and *how* certain behaviour comes about. The CROSS model adds a new dimension by including the cognitive level. In this way, a richer description of behaviour generation can be given. Modelling crowd behaviour involves identifying relevant factors and processes at three levels (i.e. the group, individual and cognitive levels) and translating the effect into the cognitive level.

The following sections will describe the relevant factors for each level for the festival scenario, starting from the group level working down towards the cognitive level. Most detail is provided on the cognitive level, as it entails the translation of how the factors at the other levels can affect an individual.

3.1 The group level

At the group level a crowd can be described from a macro view. Imagine being at a festivalor the beach festival described in chapter 1 and observing the crowd from above. From this perspective crowd behaviour can be observed in terms of behaviour patterns. To be able to say more about the situation, the context in which the individuals are situated must be included in the description of crowd behaviour. The context defines both a physical and a social environment for the individuals. The relevant factors from the physical and social environment that are relevant to crowd behaviour are incorporated in the CROSS model. They will be identified in the following sections.

3.1.1 The physical environment

In a crowd, individuals have gathered at the same physical location. All objects are part of the physical environment, including the individuals themselves. In the literature, several physical factors have been linked to crowd behaviour, such as density

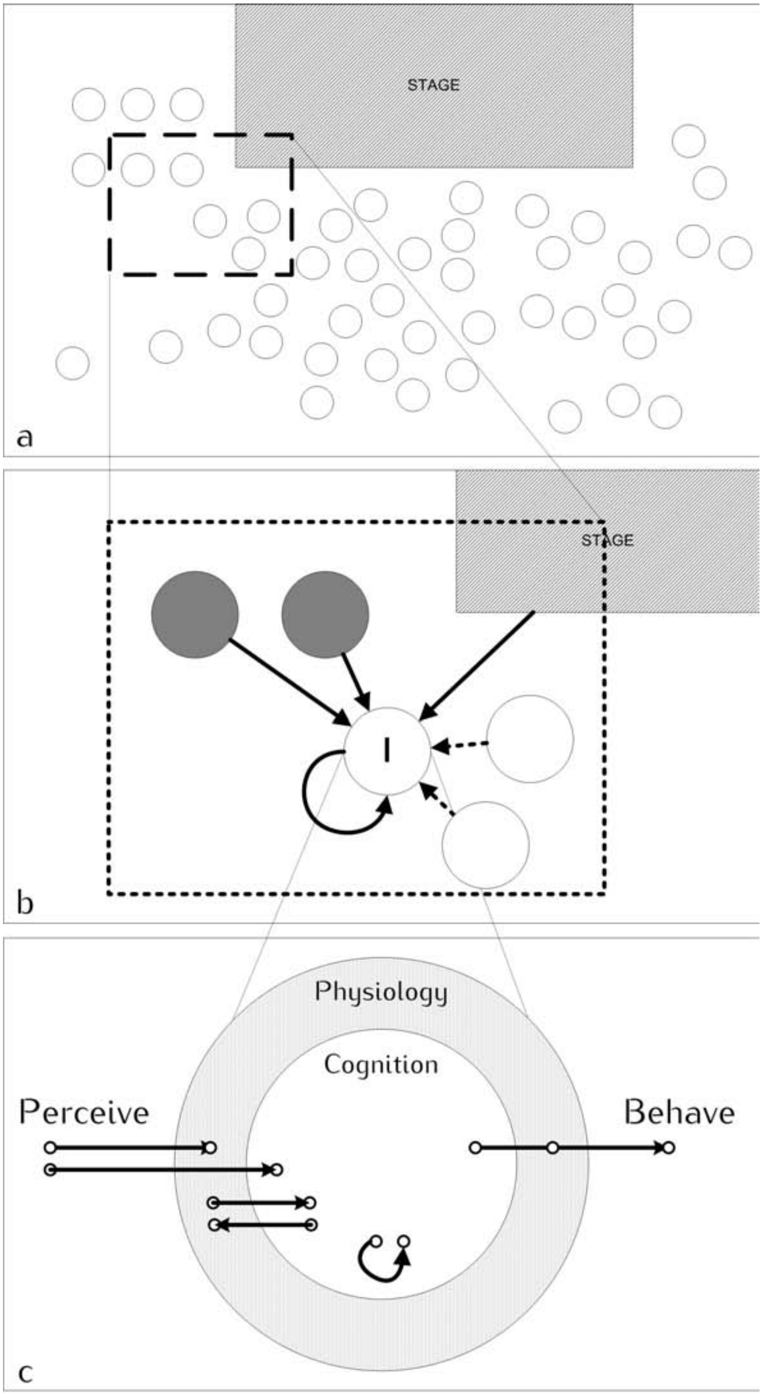

Figure 3.1: The levels at which crowd behaviour can be studied. The group level (a) where behaviour patterns emerge; the individual level (b) where behaviour is generated and the local influences of the physical and social environment originate from; and the cognitive level (c) where the individual is affected.

(persons/m^2), noise, scent and weather conditions. Safety-related research on crowd behaviour is dominated by relating physical influence factors to behaviour (e.g. pressure, density, obstacles). In safety design, movement, flow and physical impact are mainly being studied from an engineering perspective (Sime, 1995). For example, an engineering approach would involve designing a building in such a way that paths and obstacles (fences, walls, etc.) will guide people, allowing them to leave quickly or to keep a steady flow. These design features evolve around manipulating human density and maintaining a density level far from one that leads to injury or death. Human density, i.e. ρ_{human}, is an obvious characteristic of crowds that cannot be neglected as a factor influencing behaviour. Therefore, density must be incorporated into the CROSS model. It will be dealt with in more detail below.

In research on riots, *noise*, *scent* and *weather* conditions are emphasised as relevant factors (Krahé, 2001; van de Sande, 2006). Noise and unpleasant scents appear to act as intensifiers in an already tense situation (Geen & O'Neal, 1969; Rotten, Barry, Milligan, & Fitzpatrick, 1979). Regarding weather conditions, several factors can be related to the type of weather, including temperature, atmospheric electricity and rain. For example, there seems to be a relationship between violence and temperature, with more violence in summer than in winter (Anderson & Anderson, 1998; Anderson, Bushman, & Groom, 1997). A similar correlation can be found between violence and atmospheric electricity (Charry & Hawkinshire, 1981). However, bad weather, i.e. cold, windy, foggy weather, seems to have a dampening effect on aggression in crowds (van de Sande, 2006). The weather seems to have an inverted U-shaped relationship with aggression. Extreme cold or hot temperatures will prevent aggression from happening, as the need to protect one's body from extreme temperatures will be dominant.

The above mentioned factors are the ones that are most often discussed in crowd research. In the CROSS model the choice was made to include density, as it has a direct impact on behaviour at the individual level, especially on freedom of movement and on behaviour patterns. For the other factors, it is less clear how they affect the behaviour of individuals and thus behavioural patterns at the group level. Furthermore, at this point in time the aim of the study is not to acquire a complete model in the sense that all relevant factors are incorporated, but in the sense that the relevant mechanisms that underlie crowd behaviour patterns should be reflected.

Density

Several theories relate density to crowd behaviour. Although the notions of density and crowd behaviour are the common denominators, these theories tend to focus on different types of crowds, e.g. extremely high-density crowds, uniform crowds or crowds in which a riot occurs, or they tend to explore different kinds of effects, e.g. long-term versus short-term effects. Lastly, different types of explanations are chosen either in terms of physiology or psychology notions. It is important to be aware of the differences and the range of explanations when applying existing theories to explain density. The focus in this thesis lies on the direct (i.e. short-term) and local effects of density on behaviour. Within this framework the existing theories will be judged on relevance.

Theories differ in focus on the type of crowd phenomenon. The first difference in focus concerns the crowd phenomenon dealt with in this thesis. Most attention is being paid to extreme or remarkable crowd situations, such as extreme high density levels, uniformity in behaviour, or violence. Research on safety management (Kemp et al., 2004; Kemp, Hill, Upton, & Hamilton, 2007; Fruin, 1985) mostly focuses on gaining knowledge to avoid extremely high density levels, keeping the human beings involved from bodily harm. The physical impact of density plays a crucial role in these extreme settings. However, a focus on physical impact only is not enough (Sime, 1995). Behaviour is not only driven by physical characteristics, the social context plays an important role as well and must be included in order to understand human behaviour in a social setting. Other research concerning density focuses on a phenomenon called *contagion*, which refers to uniform behaviour in a crowd, for instance applause. Theories dealing with behaviour contagion describe the circumstances under which a behaviour spreads within a group, like a disease contaminating others. Although the explanation remains rather speculative, Freedman et al (1980) relate density and size to behaviour contagion by indicating that these relatively simple environmental factors can be major determinants for contagion in groups. In addition, crowd research concentrates strongly on riots[2]. There is a tendency exists to assign a link between riots and density, whereas in reality there is no such direct link between the level of density and the probability of a riot. Indirectly, density can be regarded as an intensifier in a given situation, intentisfying the situation in a positive or a negative direction (Freedman, 1975). The focus that is employed by the existing studies can be described as too specific (e.g. a focus on physical impact, contagion or riots) for the general nature of this thesis, which is aiming to understand the formation and change of identifiable subgroups (behaviour clusters). To focus on a specific crowd event, such as applause, is not general enough for the level of explanation that is sought in this thesis. Focusing exclusively on the events after a performance, for instance, will not bring insights into the behavioural dynamics during an entire festival event. To gain an understanding of what is going on in a nonextreme or pre-extreme crowd situation, it is crucial to include the relevant context that affects behaviour.

Theories differ in focus on the effect of density. Apart from their different focus on types of crowds (e.g. emergency, uniform, riots) existing theories also differ in their focus on effects of density in terms of long-term or short-term effects. Not only the research conducted in the field of safety management, but also behaviour contagion research, focuses on the short-term effects of density on behaviour, a focus that is shared in this thesis. However, theories that describe long-term density effects are found in environmental psychology, where the notion of *crowding* is employed (Stockdale, Wittman, Jones, & Greaves, 1978; Severy, 1978; Schweizer-Ries & Fuhrer, 2006). Crowding describes the psychological effect of the perception of density[3] on behaviour. The way density is perceived differs from one person to the another. To give an example, some people might find a crowded festival uncomfortable, while others experience these high levels of density as nice. In crowding

[2] Riots are crowd situations in which (a part of) the crowd is involved in aggressive and/or violent behaviour.

[3] Density is a physical measure that is observed in terms of number of people per m^2, a the physical measure.

theories, the positive or negative experience of perceiving density is considered as an important factor. Research that takes crowding into account tends to focus on the long-term psychological effects of being exposed to high-density levels. An example includes a study of Milgram (1970) where he analysed the effect of living in the city versus living in a village using the notion of crowding. According to Milgram, city life, i.e. high density, can be experienced as an overload leading to mechanisms that give rise to typical patterns of city life (e.g. pace, helpfulness). However all mechanisms need more closer examination. Even though crowding research concerns a completely different scope in explaining crowd behaviour, it does address an important point: the subjective aspect of perceiving density.

Theories differ in the type of explanation The theories discussed tend to explain either a relationship between density and physiology or between density and psychology. Both safety management and Freedman's (1975) behaviour contagion theory describe density to affect physiology, whereas crowding describes a psychological effect. In safety management, what psychologically moves an individual is often not taken into account in the design of safe spaces. This is however necessary when the aim is to improve safety (Sime, 1995). When the scope of explanation is too narrow due to a focus on the physical side, one is not able to understand behaviour and thus unable to contribute towards safer surroundings. The Love Parade incident described in chapter 1 clearly illustrates the limitations of a purely physical focus. However, physiology (i.e. the physical side) cannot be ignored either. As simplistic as its the role might be, the bodily effect of being in high-density areas is strong, by the restrictions in movement and pressure that is created. As both physiology and psychology are important, their role and interplay should be included instead of being isolated when explaining crowd behaviour.

3.1.2 The social environment

A crowd is by definition a social phenomenon as the presence of other persons instantly establishes a social setting. A description of the social environment involves a social structure specifying the group composition which is based on the type of relationships that exist between the individuals in a group, such as friendship relationships, in-group/out-group relationships and power relationships, e.g. leader-follower relationships. Crowd events can be very different, recall the descriptions of the beach festival, the shopping crowd, the supporters of a sports match and the emergency situation at the Love Parade in chapter 1. The beach festival shows an audience and LEOs. Within the audience, small groups of friends and family (i.e. companion clusters) can be identified, but also in a group of football supporters. In the mall on the other hand one can only find companion clusters and single individuals, whereas at the football match two groups of supporters can be identified. Defining the social environment shows the different ways individuals are related. These relationships between individuals are an important factor influencing behaviour.

In most crowd research, the social environment is emphasised, except for the safety research mentioned where mainly the physical environment[4] is emphasised.

[4]In safety research, the need to incorporate the social environment is receiving more attention in order to improve safety management (Sime, 1995).

The social environment in public order studies, however, is described in terms of the presence of identifiable groups and the relationships between these groups as an indicator for potential disorder. Both ESIM (Reicher & Levine, 1994) and Adang's (Adang, 1998) model, discussed in chapter 2, describe the initiation and escalation of violence as a consequence of a relationship gone awry.

Descriptions of crowds often involve a social structure in terms of friendship, in-group/out-group settings and power relationships. Friendship, for instance, is mentioned in relation to small groups of 2, 3 or 4 people who attend an event, e.g. a festival (Aveni, 1977). These companion clusters indicate the importance of being with acquaintances. An in-group/out-group setting, for instance, characterises a typical riot setting of two clearly opposing groups, where the individuals composing the groups perceive each other in in-group or out-group terms (van de Sande, 2006). The presence of an out-group makes in-group membership more salient, which gives rise to the so-called *in-group/out-group bias*. This bias reflects the tendency of group members to selectively favour the in-group, while looking more negatively upon the out-group (Forsyth, 2006). A second concept is the notion of power relationships, which is used to describe individuals in terms of initiators, leaders, or hard-core members versus followers or hangers-on. As Van de Sande (2006) points out, this notion can be viewed as a social structure of power and role relationships. Empirical data (Adang, 1998) allow to distinguish between behaviour patterns by describing individuals in terms of followers, hard-core groups and bystanders. Heterogeneity of behaviour in a crowd is thus confirmed. However, to our knowledge no theories concerning the role of power structures in crowds have been developed.

The social factors of in-groups and out-groups, power and friendship are all considered to be relevant and would in principle deserve to be incorporated into the CROSS model. For reasons of simplicity only friendship and leadership as a power-relationship are included. As indicated earlier, this thesis does not aim to be complete by encompassing all relevant factors.

Leadership

Leadership is an area that has been studied quite extensively by the social sciences. See Northouse (2004) for an overview. In general, theories on leadership focus on the leader itself by defining what attributes a leader must possess (*the trait-approach*); what kind of behaviour is required (*the skills* or *style approach*) in a given situation (*the contingency approach*); or what kind of interaction (*the transformational approach*) is required for good leadership. Leadership generally refers to a process in which an individual exerts more influence on others than is being influenced by those others. Though in this sense, all theories use the same notion of leadership, they explain it very differently, as leadership is seen as a personality trait, a skill or as the situational product of an individual being a leader.

Theories differ in the explanation of leadership. Most research focuses on explaining what it is that makes someone a leader. This seems to be driven by the need to be able to identify a good leader on the base of systematic knowledge. There are four types of leadership theories (Northouse, 2004) that define what makes someone a leader; they are based on trait, skills, situation and interaction effect. The first type of theory is called the *trait approach* that regards leadership as something innate, a person is born as a leader. The focus lies on associating attributes with leadership. The identification of attributes includes physical factors (e.g. height, appearance), personality (e.g. extroversion, self-confidence), and abilities (e.g. speech fluency, intelligence) (Bryman, 1992) . The trait approach fell in disfavour, as the findings were often weak, ambiguous or contradicting, and it thus failed to generate a list of leadership traits. The second type of theory focuses on skills that must be acquired to be a effective leader, the *skills* or *style approach*. These skills are considered to be learnable, which makes leadership available for everyone. Just like the trait approach findings from this approach were inconsistent. The third type of theory is the *contingency* or *situational approach* that focuses on the context, i.e. the situation in relation to the leader that arises. The contingency approach was a response to the difficulties of the skills or style approach. As it became clear that the explanation was more complex than a simple correlation between style and outcome. The approach has been particularly successful for practitioners, but has been criticised for its unstable theoretical basis due to the lack of body of published research. The fourth and last type of theory in leadership research is the so-called *transformational leadership approach* or *the new leadership approach*. This theory is a current approach that describes a leader as someone who is able to change and transform individuals with regard to emotions, values, standards, goals, motives, etc. The theory describes a process between leaders and followers and stresses the role of the follower. However, this type lacks conceptual clarity and the measuring used for its validity is not fully established yet.

Crowd behaviour is a complex social phenomenon in which the interaction between individuals must be involved in order to understand the social system. Existing studies on leadership neglect the role of a complex system such as a crowd. When incorporating these theories into the approach taken in this thesis, several problems arise. First of all, leadership will be addressed in a crowd context, not in an organisational context of a company for instance. Secondly, the research question is different. This thesis focuses on how a leader influences an individual, whereas all theories, except for transformational theories, are aimed at identifying what makes someone a successful leader. Thirdly, and most importantly, leadership is in this thesis regarded as a product of a reciprocal process that involves both leaders and followers (Barrow, 1977; Hollander, 1985; Hollander & Offermann, 1990; Hollander, 1993). Most theories doe not include this aspect. The main critique that the present-day approaches receive involves this reciprocal process, as these approaches lack conceptual clarity and explanatory power (Northouse, 2004). A direct answer to the question ‘how do leaders in a crowd directly influence other?’ (i.e. in the short-term and with direct behavioural impact) remains unanswered.

3.2 The individual level

The individual level represents the level at which behaviour arises. Individuals interact with their environment by perceiving and acting. Including factors that play a role in this interaction is therefore important in describing behaviour in crowds. As both individuals and their physical positions are unique, their perception and behaviour

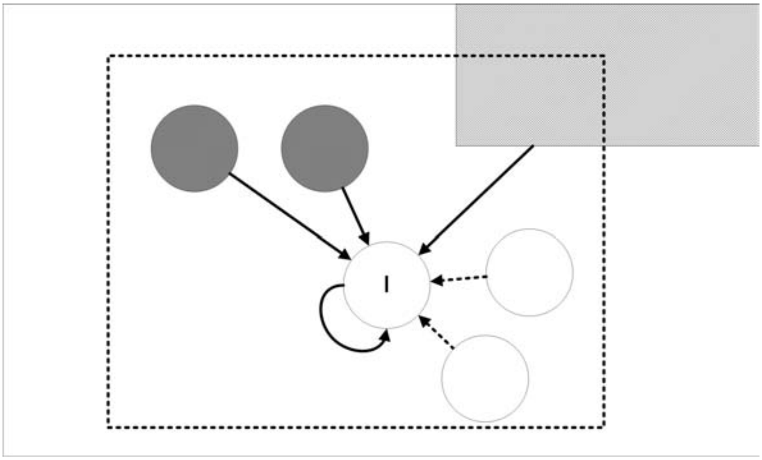

Figure 3.2: An individual in a crowd is influenced by himself and by his physical and social environment. In this social environment, the influences vary, depending on the relationship between indivduals.

will differ. Based on what an individual perceives, his internal state is affected. Based on the internal state at that moment a particular kind of behaviour is chosen[5]. Theories that describe individual behaviour without any reference to an internal state are rare. However, an example includes the traditional behaviourist theories that describe behaviour as reflexes, such as Pavlov's classical conditioning theory (Pavlov, 1927). The internal state is not taken into account as it cannot be measured or observed (Watson, 1930), or it is regarded as nonexisting. The social sciences have abandoned these black-box approaches (Jorna, 2000) by including the internal state. In short, approaches can be said to range from very simple attributions (e.g. personality psychology, economics) and mental ascriptions (e.g. social psychology), to complex cognitive structures and neuromapping (e.g. cognitive psychology).

In figure 3.2 the influences on behaviour are visualised. It is important to note that the influence of environmental factors is local. This is true for both the physical and the social environment. However, the social environment can also involve group-level influences, through the existence of subgroups for instance. The local physical environment of an individual consists of physical objects. In the festival context, the physical environment involves the physical presence of other people, a stage, bars, toilets, fences, walls, etc. The physical characteristics of individuals on the one hand and the interplay between these characteristics and the environment result in restraints in both perception and behaviour. For instance, our eyes' range of sight makes it impossible to see what happens behind us, i.e. a physical object, such as a wall, directly restricts movement. Applying this individual-level notion of local influencing, density should be regarded as a local factor influencing individual behaviour. When density is high at group level, this does not necessarily imply that each individual is at a high-density location. Similarly, when density at group level is low, local density can be

[5]As a reminder, the use of the word 'chosen' does not imply a conscious choice: it implies that behaviour is a consequence of certain internal and external processes.

high, e.g. when a number of individuals are standing at the bar.

The social environment involves other individuals. Both the relationships between an individual and others and the perceived relationships between others represent the social environment of an individual. Relations can involve simply co-presence, membership of the same group or subgroup, or being friends or family. Perception of the social environment also involves aggregates that are perceived by the individual itself[6]. However, for the sake of simplicity, these group-level perceptions will not be taken into account in the CROSS model. Only the perception of context-relevant items, such as the stage, toilet, bar and friends will be included.

Perceiving behaviour of other individuals in the local social environment may also influence an individual. How perceived behaviour influences behaviour depends on the relationship between the perceiving and the observed individuals. For instance, being with friends has a different effect on behaviour than seeing a leader.

The situated individual

The interplay between the physical and social environment and the internal state of an individual gives rise to behaviour. The role of the internal and external state of an individual is captured in the term *situatedness* (Wilson & Keil, 1999). Situatedness is a term adopted from the cognitive sciences, where it is used to indicate that the behaviour and cognitive processes of an individual are first and foremost the outcome of a close coupling between agent and environment (Lindblom & Ziemke, 2002). In cognitive sciences the term is mostly used as physical situatedness. In this thesis, situatedness will refer to both physical and social situatedness. In that sense, the tendency to overestimate the influence of personality and underestimate the role of a setting in crowd situations (van de Sande, 2006) will be explicitly avoided. Influences on behaviour are considered dynamic and thus variable over time. A certain setting defines whether the main influence is either external, internal, physical or social.

A situated individual is both embodied and embedded (Wilson & Keil, 1999). *Embodiment* means having a human body, including all the behavioural and cognitive constraints that it entails (Ballard & Sprague, 2007). When attemtpting to understand or explain behaviour, it is important to be aware of these constraints, because your eyes determine what you can perceive, and your mental state determines how this perceived information is processed and how it affects your behaviour. *Embeddedness*, however, refers to the fact that an individual is always present in a specific context and that he is influenced by situational factors. These factors could be stable, such as the nationality of a person or his culture, or more changeable and linked to the knowledge or norms (i.e. rules of conduct) a person has. Social embeddedness relates to the social relationships of an individual, e.g. with friends or leaders. Embeddedness stands for the link between the internal world and the external world. Being embedded is what is taking place in one's head while being in a certain context.

For the CROSS model, the notion of situatedness has direct consequences for the way perception is dealt with. As a result of being embodied and having an internal state, limited and subjective perception can be distinguished. *Limited perception* re-

[6] The three levels according to which crowd behaviour is described and viewed given the three levels correspond to how an individual perceives a crowd he is part of. He will observe patterns, but also see the heterogeneity: some parts are more detailed than others.

stricts the way an individual perceives the world due to the physical constraints of being embodied or physically embedded, e.g. a tree in one's line of sight blocks a part of the perception. This affects what an individual knows and therefore how he is influenced by the world. Consequently, individuals will always have 'incomplete' information. An example of this awareness is the notion of *bounded rationality* (Simon, 1957). Bounded rationality refers to the cognitive and ecological limitations of both knowledge and the processing capability of individuals that play a crucial role in their behaviour. To neglect the fact that people do not have complete information would make their real behaviour puzzling, as 'rational'[7] behaviour is expected. The acknowledgement of bounded rationality results in the differentiation of what influences an individual. Limited perception functions as a filter that discerns what information can be obtained by an individual. Perception is bounded by the spatial position at that moment, heading and specific limitations, such as gaze width, gaze depth, and hearing range. *Subjective perception*, however, describes the way information is interpreted taking into account the situational constraints. The restrictions in perceiving the world involve both previous experiences as well as the internal state of an individual at that particular moment. The 'subjective' perception requirement can be seen as a filter on 'objective' perception, i.e. a cognitive lens. Heterogeneity among individuals then becomes important, as each person has his own unique experiences and therefore his own unique filter to watch and interpret the world around him.

In short, the view of a situated individual in a crowd stresses the importance of incorporating both external and internal relevant factors. All external factors exert their influence on behaviour by affecting the internal state. On the other hand, the internal state itself shapes the way that information affects the internal state. When processing all influences, the external factors must be 'translated' into an intra-individual level to take effect. Figure 3.2 shows the individual level of behavioural influence, describing an individual being influenced by his physical and social environment and by himself. The remainder of this chapter will deal with the cognitive level of an individual in a crowd, providing a structure that allows for the translation of external influences to take effect as well as the relevant internal factors and processes.

3.3 The cognitive level

The cognitive level describes the way an individual processes knowledge in order to determine behaviour. The behaviour selection follows Newell's *principle of rationality*: actions are selected to attain the individual's goals (Newell, 1982). To describe crowd behaviour, this chapter started out by distinguishing three levels of descriptions (the group, individual, and cognitive levels). The cognitive level is further specified in this section. A multi-level analysis is considered necessary in this thesis. Defining multiple levels of description is considered a common method, for instance, from the biological to the cognitive, rational and the social levels of description (Newell, 1990). Three different levels can be distinguished to represent the internal world of an individual:

[7] Rational behaviour is in this context regarded as the view that individuals will always choose the optimal behaviour provided that they have complete knowledge of the world.

The intentional level ascribes beliefs, desires and intentions to persons in order to explain and predict human behaviour (Dennet, 1978, intentional stance). It concerns an abstract explanation of the behaviour of others by inferring between what we see and what we know of the situation and/or person. Theories in social psychology often operate on this level. The knowledge level (Newell, 1982) is substantially the same as the intentional level (Newell, 1990).

The functional level describes cognitive mechanisms and representations of an individual in order to explain behaviour. The description of the cognitive mechanisms entails an empirically validated theory (Anderson & Lebiere, 1998). Theories in cognitive sciences focus on this level, although they incorporate the other levels as well.

The physical/physiological level explains behaviour in terms of physical laws, chemical reactions, or physiological properties (Dennet, 1978, physical stance).

Each level (intentional, functional and physical) describes behaviour but differs in the amount of detail and precision. The theories concerning the intentional level tend to be more abstract and linked to a specific type of behaviour (e.g. violence, fleeing). The differences in precision and detail make it hard to integrate and combine the levels, as the lack of unifying theories shows. The aim of this thesis is to develop a concrete and generic model of crowd behaviour. Both the functional and the physical/physiological level will be adopted as they enable to merge existing theories of crowd behaviour. Furthermore, at the functional level, the individual is considered as a cognitive system that allows to adopt a framework within which the integration and translation of theories can take place. Cognitive sciences is the research area that aims to understand the human mind, focusing on conscious and subconscious mental processes, knowledge possession, knowledge storage, knowledge change, information processing, etc. The tendency in cognitive sciences is to work on a general theory of cognition. Examples include neuroinformatics (neurosciences and AI), neuropsychology (neurosciences and psychology), psycholinguistics (linguistics and psychology), computer linguistics (linguistics and computer science), and architectures of cognition (psychology and AI) (Hendriks, Taatgen, & Andringa, 1997; Posner, 1989). A generic theory that focuses on the interface between psychology and artificial intelligence relates best to crowd research, as it includes both situatedness and social phenomena at the group level. In cognitive sciences, theories are developed and tested within a larger structure representing a blueprint of the human mind, i.e. a cognitive architecture. A cognitive architecture describes the functional components that cooperate to process information, resulting in behaviour.

Examples of such architectures include ACT-R (Anderson & Lebiere, 1998), Soar (Newell, 1990), and Clarion (Sun, 2003). They all incorporate a structure in which the use, representation and change of knowledge is described in great detail. The level of detail enhances the explanatory power. In addition, these architectures are empirically validated, which makes the rich explanation cognitively plausible. These architectures have a unifying nature, representing a structure into which theories can be integrated and translated. They focus on the valid description and reproduction of higher cognition, such as learning and planning tasks, whereas this study focuses on understanding behaviour. Compared to these architectures, the context of the individual is crucially different in this study. In cognitive sciences, an individual is studied in the context of performing a specific task, for example learning a language, whereas this thesis involves a crowd context. Moreover, embedding an individual in a social context is what distinguishes this study from most other research in the cognitive sciences (Sun, 2008). As embodiment is acknowledged in cognitive sciences, these architectures do incorporate 'physical situatedness' in terms of embodiment[8] but the role of social embeddedness can only be found sporadically in cognitive sciences. Some exceptions are CLARION of Ron Sun (2000), and RBOT of Martin Helmhout (2006).

The focus on higher cognition in cognitive architectures does not cover the relevant cognitive processes and tasks of an individual in a crowd. For instance, planning what one is going to do next week is not a process that needs to be involved to understand behaviour at a certain moment in time based on the settings at a certain moment in time in a crowd. In this study, only those aspects of a cognitive architecture that are considered to be relevant to crowd behaviour will be used (see below). In addition, a new element will be added: a cognitively plausible framework wil be used and filled with social theories. In this manner, the way in which an individual is dealing with his social world will be translated into functional terms.

Cognitive architectures have a strong explanatory power due to their high level of detail, plus they are empirically validated while using a generic framework. The structure of these cognitive architectures will be adopted in the CROSS model. In CROSS , an individual will therefore be represented as a cognitive system in terms of 1) architecture, 2) representations, and 3) processes, which is a division often used to describe human cognition (Helmhout, 2006). In general, these elements are used to describe human information processing. The architecture refers to a structure in which the representations and processes are placed. It includes the body of an individual with its physiological aspects, including the senses. The representations on the other hand contain information that is located in memory. The knowledge in memory allows an individual not only to understand the world around him, but also to act in accordance with a context and internal state at a given moment. The processes represent the dynamic aspect of the cognitive system, i.e. the interaction with the external environment by perceiving and acting. Perception involves receiving input via bodily sensors, whereas action concerns the behavioural output of an individual. The description of behaviour will be restricted to defining the relevant factors, characteristics or mechanisms that are either part of the architecture, representations or processes. In the following section, the different parts of the cognitive system of an individual in the CROSS model will be described, including the relevant aspects concerning the crowd context.

3.3.1 Architecture | physiology

The architecture represents the structure of cognition (Newell, 1990). It is the place where an individual's memory (representations) and processes (perception and be-

[8] The role of embodiment has in fact caused a fundamental shift in cognitive sciences towards the end of the eighties (Pfeifer & Scheier, 1999). Cognition used to be studied in isolation from the environment. This provoked a counter movement in embodied cognition, e.g. the subsumption architecture (Brooks, 1991). It was acknowledged that cognition could not be studied in isolation from the real world in which individuals are situated.

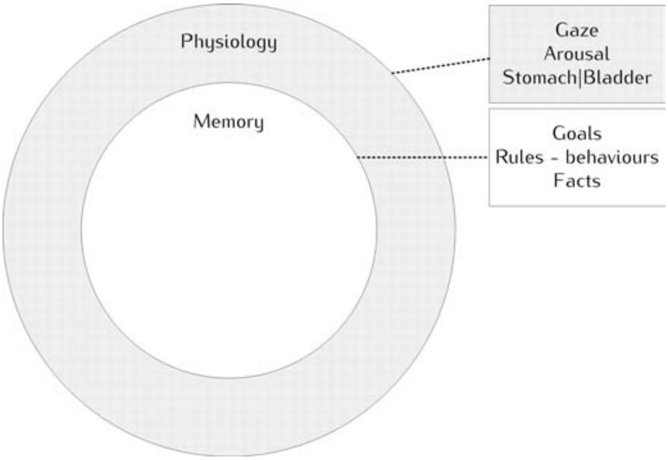

Figure 3.3: The cognitive framework that represents the internal world of an individual comprises physiology and memory.

haviour selection) can be found. The architecture also involves the physical properties of the natural system, it is embodied[9]. To represent behaviour in a crowd, there is no need to incorporate the whole functioning of the human body. Being embodied implies having behavioural and cognitive constraints. Not only does human anatomy define an individuals's perceptual range and behaviour options (e.g. a hearing capacity of 20 to 20,000 Hz, not being capable to fly, etc.), it also has an impact on mental processes. Furthermore, several physiological factors, such as arousal, energy level, alcohol and drugs use, appear to be relevant in a festival context, as they affect behaviour via physiology (Challenger et al., 2009b; Wijermans, Jorna, Jager, & van Vliet, 2007; van de Sande, 2006).

Arousal is the attentional state of an individual, a state of alertness that is low when a person is sleepy, normal while being awake under normal conditions, and high in stressful or exciting situations. The notion of arousal involves the physiological measure of the heart rate and blood pressure of a person. This physiological state is related to an important basic mechanism of our sympathetic nervous system, namely *fight or flight*, which prepares us to act fast in a situation of threat (Baron & Richardson, 1994). Arousal often pops up when discussing riots, especially in relation to aggression (Berkowitz, 1981, 1988; Zillmann, 1988). Arousal also affects behaviour through the impact it has on information processing in demanding and complex situations. Under these circumstances, arousal increases and is associated with narrowing attention (Sanbonmatsu & Kardes, 1988). The resulting behaviour is limiting our perception. For instance, under dangerous circumstances, the emergency exits plates may not be registered and used in finding the way out. Arousal is considered in this thesis as a neutral state of alertness that supports an individual in dealing with a dynamic and complex environment, and should not be understood in a positive or negative valuation.

[9] To put it in Newells words: "the architecture involves both hardware and software" (Newell, 1990, p. 80).

Energy is another important physiological measure that relates to the bodily resources of an individual. Energy is a necessary resource for life, enabling an individual to behave, think, recover, etc. A low energy level may direct people towards the decision to leave the crowd to get food, drinks or to rest and to restore the energy level. In a festival context, drinking and eating are relevant kinds of behaviour, and therefore the corresponding physiological elements of having a *bladder* and a *stomach* can be considered relevant. This brings us to the issue of *alcohol* consumption, which is obviously relevant in a festival setting, but often also linked with the occurrence of group violence. Even though there is no direct or simple causal relationship between alcohol use and aggression, evidence shows that a small amount of alcohol may lead to increased aggressive behaviour (Baron & Richardson, 1994; Russel, 1993). Other substances, such as marijuana, XTC or LSD are also relevant in a festival context. Marijuana seems to decrease the probability of violent behaviour, as it makes an individual less aware of his social surroundings (Baron & Richardson, 1994). However, the effect of drugs other than alcohol on behaviour, such as aggression in crowds has not been well explored (van de Sande, 2006)[10].

Although many of the physiological factors mentioned are potentially relevant in a festival crowd context, it is mostly the group level correlations that are reported (rather than causality). For instance, the relationship between alcohol and aggressive behaviour appears to be positive (Baron & Richardson, 1994; Russel, 1993). However, the actual explanation of the relationship between alcohol and aggression in terms of influences on the intra-individual level remains open for discussion. For the CROSS model, the choice was made to incorporate only the most essential elements first, and to leave out elements for which there is no empirically validated theory. In this model, the incorporation of physiological factors or characteristics will therefore be restricted to limitations in perception (i.e. gaze width and depth), to arousal and to the possession of a bladder and a stomach. Limited perception involves a crucial filter on perception that cannot be neglected in describing behaviour. This filter is also a direct consequence of being embodied (Ballard & Sprague, 2007). Arousal corresponds to primitive/basic behaviour that is related to short-term survival mechanisms (e.g. fight/flight, (Baron & Richardson, 1994)). It allows human beings to respond to a potentially life-threatening situation. The bladder and stomach are factors that are relevant to the context. As people eat and drink, these represent the physiological characteristics to embed the festival context in an intra-individual level. Therefore, they must have a certain effect.

3.3.2 Representations | memory

Individuals use representations to be able to live in a complex and dynamic world. In the CROSS model, representations are represented by a memory structure. Memory represents the knowledge an individual has as well as the processes describing both the changes in the content of the representation and the interaction with the world. In this study, the concept of memory is based on the memory theory of Anderson et al. (2007) which lies at the base of the ACT-R architecture (Anderson & Lebiere, 1998). This theory describes how memory works in functional level terms, how mem-

[10]This is interesting, as the research report on the beach festival riot discussed in chapter 1, relates to the importance of both alcohol and drugs (Muller et al., 2009).

ory elements become more dominant (i.e. more highly activated) and play a role in behaviour. It describes how memory elements change (i.e. learn), and how they result in typical human errors in performing or learning tasks (e.g. in short term memory tests, or language learning). But also what the distinction is between declarative and procedural knowledge. The following sections will describe memory and its content for the CROSS model.

Memory

Memory consists of memory elements that together provide an individual with an internal representation of the world that allows him to interact with his environment. A memory element has two important properties: 1) it has content and 2) it has an action level (i.e. dominance). Three types of memory elements can be defined namely *goals*, *facts* and *rules*. Content refers to knowledge and how it is used. The activation level reflects which memory element will be more likely to affect behaviour. Both content and dominance of a memory element will change over time. A change in content represents learning, forgetting or reorganising, whereas a change in dominance represents what is of influencing behaviour at a given moment in time, i.e. the internal state.

All knowledge, i.e. the content of an individual's memory elements, is represented in either a goal, a fact or a rule. These types of memory elements imply that knowledge is a concept that does not only convey factual information, but also incorporates actions[11]. A goal represents the desired state of an individual, making certain behaviour more or less relevant to choose. Facts, however, represent a piece of factual or declarative knowledge[12], a so-called chunk (Anderson & Lebiere, 1998). This kind of knowledge assists an individual in interpreting what he sees or distinguishing which behavioural option is preferable or more relevant given a particular situation. For example, when seeing a glass of beer, knowledge about beer and what it looks and smells like allows an individual to identify it as beer. When one is thirsty, the knowledge that this liquid is drinkable together with the experience of liking the taste, might lead to the choice of drinking the beer. However, knowing that the glass of beer belongs to someone else would lead to the choice of not drinking the beer. The last type of memory elements concerns *rules*. Rules involve the internal representation of actions, i.e. procedural knowledge. These representations can reflect a description of behaviour, like drinking or walking, but also an internal action, such as changing the content of a memory element, i.e. learning or reorganising.

The activation level of a memory element indicates the dominance of that element, and also how easy it is to access the content of this element. In that sense, forgetting involves the decay of the activation level below a threshold range, which means that the element is no longer retrievable. It is important to realise that the activation mechanism is related to the activation of memory components, as in a cognitive system only what is dominant will affect behaviour[13]. This is the functional interpretation of the concept of *saliency*. Saliency is a notion from psychology that is used

[11] In that sense, an individual knows how to breath, which does not mean, however, that he can describe how breathing in the human body works.

[12] The word 'knowledge' often refers to facts or declarative form of knowledge.

[13] In that sense, telling someone "you know you shouldn't.." is not logical, as the knowledge should be salient.

to describe why certain behaviour (e.g. normative behaviour) arises in a particular setting. It relates to the phenomenon where a mental concept, such as specific norms or a specific identity, is in focus and therefore has more influence than other norms or identities (Kallgren, Reno, & Cialdini, 2000; Mullen, Migdal, & Rozell, 2003). The activation of memory elements changes over time. It increases due to perception, and it decays over time without stimulation[14]. Observing behaviour implies an increased activation of that particular cognitive representation of behaviour. Moreover, all the other elements that are associated with this memory element will be affected as well.

Goals. Human behaviour is goal directed (Kendrick, Neuberg, & Cialdini, 2005). In this thesis, behaviour will be described from an intra-individual perspective, rather than attributing a meaning or function to the behaviour that can be observed. What exactly is the internal representation of a goal that causes certain behaviour to be exhibited? In cognitive sciences, there is no clear-cut answer to this question, as Schoelles summarises: "the concept of goal has many senses. It can be used in a motivational sense; it is something we want to achieve in the future, something we are aspiring to. It can also be an endpoint for a problem-solving experience" (Gray, 2007, p. 325). Most cognitive architectures use the term 'goal' as an endpoint, as declarative control information that guides the direct interaction with the environment (Altmann, 2007). This is regarded as a goal in the sense of *intention* by Carlson (2007). In this thesis, the focus lies on understanding *why* an individual does what he does and on making explicit *how* an individual chooses his actions. This is in line with the motivational use of the 'goal' concept. Therefore, in this thesis, the definition of a goal follows the definition of motivation: *"a modulating and coordinating influence on the direction, vigour and composition of behaviour. This influence arises from a wide variety of internal, environmental and social sources, and is manifested at many levels of behavioural and neural organization*" (Wilson & Keil, 1999).

This definition raises the question of how a goal, used in the motivational sense, can be incorporated into a structure derived from a cognitive architecture? ACT-R focuses on problem-solving tasks involving executive tasks, and this differs considerably from a crowd behaviour domain involving social interaction. Therefore, in this thesis, only the structure and concepts from a cognitive architecture like ACT-R will be adopted. This structure, however, will be filled in a novel way. The reasoning that Sun (Sun, 2003) presents in his cognitive architecture Clarion (Connectionist Learning with Adaptive Rule Induction ON-line) will be followed. Clarion is different from other cognitive architectures, as it distinguishes between implicit and explicit processes and their interaction. In Clarion, goals are action-related, like in other architectures, but they are abstracted from drives, and thus provide specific motivation for behaviour. This is called 'the motivational subsystem' (Sun, 2003). In the CROSS model, the concept of goal is used as an abstract notion that is derived from the concept of 'motivation'[15]. For this reason alone, one concept will suffice, whereas Clarion employs two (i.e. drives and goals). More importantly, the model will incorporate multiple goals. In addition, the role of the changing dominance of goals due

[14] This functional description of memory elements resembles the behaviour of neurons that can also be stimulated or decay over time.

[15] This requires a translation of a motivation in terms of something an individual is aiming for, rather than being an individual's driving force.

to context will give rise to diversity of behaviour, as the relevance of a behaviour is related to the dominance of goals (Wijermans, Jorna, Jager, & van Vliet, 2008). In that sense, situatedness is reflected in goal dominance, as it is subjected to influences that depend on a particular situation. The dynamics of the goal dominance may cause perseverance in one selected behaviour or choosing another behaviour.

To select relevant goals for an individual in a crowd, knowledge is needed from the social sciences. In this study, several 'need' concepts from Max-Neef (Max-Neef, 1993) and Maslow's motivation theory (Maslow, 1943)[16] were adopted. Subsistence, safety, social and personal identity needs are considered relevant in a crowd context. Both subsistence and safety are physiologically rooted drives that are related to staying alive, eating, drinking, sleeping etc. (subsistence goal) and that protect our physical and mental safety (safety goal). At a festival, people going to the toilet or to the bar are displaying behaviour that is typically related to the subsistence goal. Hence, the incorporation of a bladder and stomach in the CROSS model. Feelings of unsafety can be quite prone when standing in crowded areas or areas that are perceived to be crowded. The social and personal identity needs relate to the focus on 'belonging to a group' and to the focus on oneself. The difference between the two is similar to the difference between public and private self or identity, which involves different behaviour associations (Baumeister, 1998). For instance, when the public self is more salient, it is more likely that the individual in question will exhibit socially desired behaviour (Stapel & van der Zee, 2006; Wiekens & Stapel, 2003). Furthermore, it has been proven that the presence of other people primes the public self and makes it more dominant (Shah, 2005). Therefore, the social environment will play an important role in determining behaviour in the model. Each need is translated into a goal, a state an individual desires to reach.

The concepts of *subsistence*, *safety*, *social*, and *identity* are translated into abstract goals that can potentially be satisfied by multiple behaviours. The dominance of these goals influences the probability of certain potential behaviour to be selected. More specifically, the dominance of such an abstract goal makes a behaviour that is more likely to satisfy this particular goal more attractive to choose. The dominance of a goal depends on the difference between the preferred and the real level of satisfaction. This preference may differ from one person to another. For example, one individual feels more comfortable in a crowded area than another. Consequently, the setting of a goal depends on the situation, but can also reflect personal characteristics, such as being easily scared. Furthermore, a dominant goal makes certain kinds of behaviours more salient and thus more probable to be selected, as behaviour selection is based on activation levels. For example, J* standing close to his friends is fulfilling his social goal. In addition, as they are drinking a beer, his stomach is filled and his subsistence goal is being satisfied.

Facts. An individual who lives in a complex environment must be able to respond adequately in order to behave adaptively. This involves not only perceiving relevant elements but also responding adequately in accordance with the input. To be able to do this, an individual needs to add meaning to what he sees, but to act appropriately

[16] The resemblance in concepts to Maslow's need hierarchy does not imply an adoption of the hierarchical structure. This thesis incorporates a dynamical hierarchy and strongly rejects the view of a fixed hierarchy (Wahba & Bridwell, 1976).

Table 3.1: The types of behaviour in a crowd, adapted from the collective behaviour table by McPhail (McPhail, 1991, p. 164).

Locomotion		Manipulation		Vocalisation & Verbalisation	
Vertical	Horizontal	Object			
sitting	walking	grasping	clapping	wailing	singing
standing	running	carrying	finger-	yeahing	
jumping	jogging	lifting	snapping	booing	
lying	marching	passing		whistling	
bowing	dancing	waving		hissing	
kneeling	queueing	throwing		laughing	
		pushing		ooh-,ahh,	
				ohhing	

he should also be able to discern between potential actions. Factual or declarative knowledge allows an individual to interpret or distinguish between people, situations or behaviours. In any crowd context specific factual knowledge is needed: knowledge of the physical surrounding (*area facts*), knowledge of people (*person facts*) and knowledge of behaviour (*behaviour facts*). In a festival context, area facts allow an individual to recognise the stage, bar and toilets. Person facts allow an individual to recognise other people, but also to distinguish between people, for example, whether someone is a friend, or whether someone is considered as a leader. Person facts play a role in perceiving and interpreting the social aspect of a specific type of physical object (a person) that shows a certain kind of behaviour. Behaviour facts allow a person to recognise a type of behaviour when he sees it, but more importantly, they include the expectations an individual has for how certain behaviour can satisfy his goals. Using this information, the behaviour selection process can discern between the kinds of behaviour that are relevant or not.

Rules. To be able to exhibit behaviour, an individual needs to know these behaviours. A *behaviour rule* is an internal representation of a kind of behaviour describing how a particular action is being performed by the body. Behaviour can be defined at a range of levels, varying from muscular movement to ballistic movements. In this study, only behaviour shown in crowds is relevant, such as dancing, singing, talking, laughing, eating, walking into different directions, standing in line, etc. In table 3.1 a non-exhaustive overview of the kinds of behaviours that can be observed in a crowd can be found as described by McPhail in his observation studies (McPhail, 1991).

3.3.3 Processes | perception and behaviour selection

In the previous section, the static components of the cognitive system were discussed. Now attention will be paid to the processes of the cognitive system in order to describe the dynamic aspect. The internal state of an individual is changing constantly due to both internal processes and the interplay between the external and internal world. The CROSS model describes the following two main processes within a cogni-

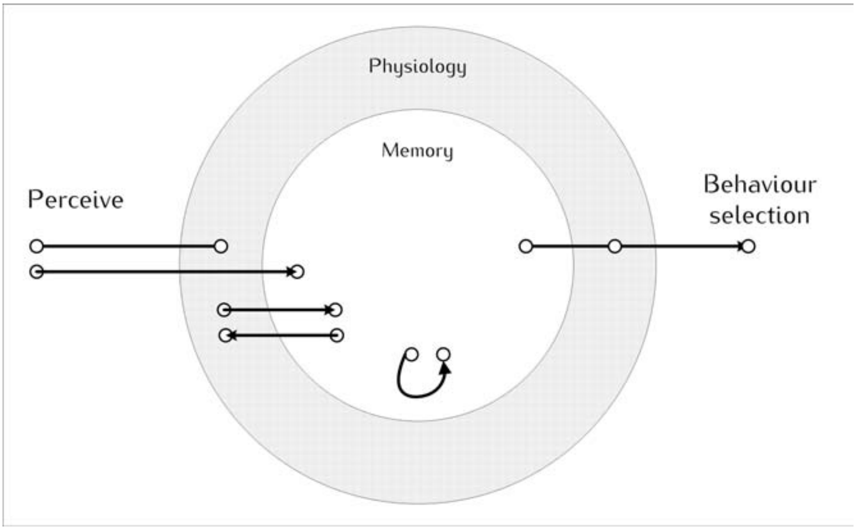

Figure 3.4: The processes within the cognitive framework that give rise to changes in the internal state (i.e. physiology and memory).

tive system: 1) *perception*, and 2) *behaviour selection*. Processes such as reasoning, thinking or deliberating can be considered part of behaviour selection. Perception affects an individual by activating and changing his physiological state or memory representations. Behaviour selection concerns the internal state at a particular moment, i.e. the content of the representations and the dominance of the elements, in order to select a behaviour. Figure 3.4 shows these main processes and the influence relationships between environment and physiology, environment and memory, physiology and memory, and within memory itself. These processes describe a continuous and parallel flow through which an individual is being influenced via perception and exerts influence on the world via exhibiting behaviour.

Perception

The moment an individual perceives, his internal state changes. In the physical world, objects and terrain are being observed, whereas in the social world, behaviours and people are being observed. In addition, the internal world, i.e. the bodily and mental state at a particular moment, is being perceived. In the CROSS model, the way perception affects the internal state of an individual is distinguished between three types of perceptual influences: the *priming*, *physiology update* and *memory update* of cognitive elements.

Priming is the increase in activation of a memory element due to perception (Anderson & Lebiere, 1998). The pure observation of an object, person or behaviour will increase the activation level of the corresponding representation. This makes it easier to retrieve (i.e. to remember) the element and thus more likely to act in accordance with the setting in question. This effect is clearly illustrated with regard to the behaviour rules. The activation levels of the different behaviours at that moment represent an order. The behaviour with the highest activation level is most likely to be chosen, but this order is dynamic as the most dominant behaviour is something that changes from one moment to the other.

Physiology update represents the change in the physiological state. The CROSS model restricts itself to arousal and having a stomach and bladder. These are updated in term of a lower or a higher level. An increase in arousal refers to a decrease in time to select a behaviour. (See behaviour selection for the details.) In addition, an increase in the stomach level reflects a full stomach, i.e. feeling less hungry. However, the bladder works in the opposite way, as a higher bladder level increases the urge to go to the toilet. Arousal is only affected by the external world. Although the fact that arousal can be affected by an individual's mental state is acknowledged, for reasons of simplicity, this second-order reflection will not be included. The stomach and bladder, however, are submerged to internal updates, as metabolism makes the stomach empty and the bladder fuller over time.

Memory update represents the change in the content of memory elements due to both external and internal perception. The change in memory element content that is based on external perceptions involves knowledge and preferences, i.e. interpretations, which act as a filter on perception. This implies that the same observation can have different effects on different individuals, based on how they interpret their perceptions (e.g. is he a friend or not?) in affecting facts, but also on an individual's preferences for satisfying a certain goal. A behaviour fact represents the expectations of a behaviour to satisfy one or more goals. On the basis of what an individual sees in the world, these expectations may change. With regard to goals, the satisfaction level is related to a current context and therefore it affects which goal is more dominant. As indicated under the physiological update, the subsistence goal is updated by the physiological state, whereas the identity, social and safety goals are affected by external perception.

Figure 3.5 visualises the influence relationships that are incorporated into the CROSS model. From the external world, these relationships convey behaviour being primed, goals being satisfied to a certain extent based on the setting at a given moment and on internal preferences, facts being updated based on observations, but they also convey the changes in physiology due to external triggers. Internal perception reflects physiology affecting the mental state as well as the mental state affecting itself.

Behaviour selection

Human beings exhibit behaviour all the time. The behaviour they exhibit is a consequence of their internal state. Behaviour selection involves a process of selecting an 'optimal' behaviour bounded by a certain amount of time. The most optimal behaviour is the behaviour that best satisfies the goal that is most dominant at that particular moment. Selecting the most optimal behaviour involves comparing the behaviours in one's repertoire to each other until all retrievable behaviours are compared or until one runs out of time[17]. Behaviours are compared to each other in a specific order. This order is based on the activation value of the behaviour rules (i.e. the

[17] To run out of time will usually be the case. This serves as an efficient way to go through search space by limiting the search in terms of time.

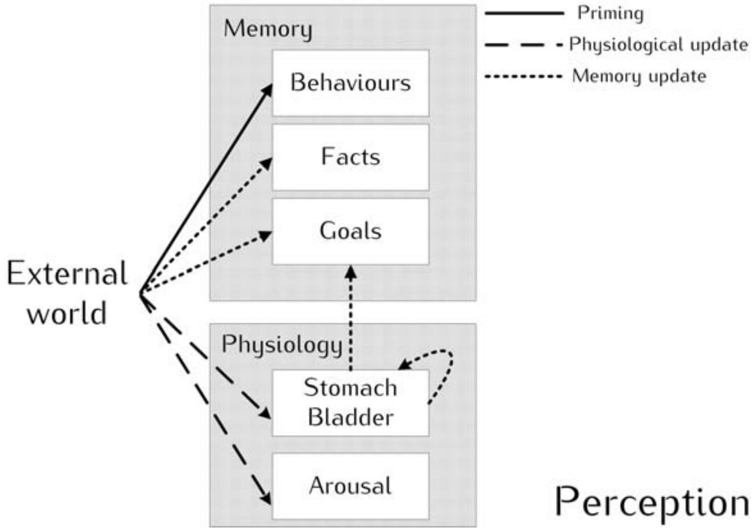

Figure 3.5: The three ways (priming, internal and external update) perception influences the internal world (physiology and cognition).

dynamical hierarchy). As activation is influenced by behaviours via perception, ordering the behaviour rules is dynamic and situated. In the behaviour selection process, time and comparison are two important notions. Time is related to the arousal level, a physiological state. Time functions as a restriction in addressing each single behaviour option and in comparing options to choose the most optimal. Comparing behaviours concerns a combination of the order of comparison, goal dominance and the knowledge of the behaviour under comparison (i.e. the expectations in the behaviour fact). The behaviour selection process is visualised in figure 3.6.

Time functions as an important restriction in the behaviour selection process. The amount of time available allows to compare behaviour and to select the most suitable behaviour for that particular moment. However, in a natural, dynamic environment, an individual will not have unlimited time to choose the best possible behaviour. He will have to find an optimal behaviour within the time available, especially in a crowd context where interactions between individuals occur at a high rate. Physiological influences, such as arousal, appear to influence this selection mechanism by increasing the 'time-pressure' as arousal gets higher. In the CROSS model, arousal is directly linked to the internal time an agent has to choose a behaviour. When arousal increases, time is restricted and vice versa. An increase in arousal results in less comparisons and thus in a higher probability for the behaviour with the highest activation level to be chosen, regardless whether this behaviour is optimal, suboptimal or even the worst choice. In this sense, an agent that has endless amounts of time will behave like a classical rational agent[18]. By describing behaviour selection

[18]A rational agent has complete knowledge. It addresses all options it has in order to select the most optimal, e.g. cost-efficient behaviour. Generally, the limitations of an individual as an information processing system is not taken into account. However, individuals do not have complete knowledge and do not have infinite amounts of time to search for the most optimal solution (Simon, 1996).

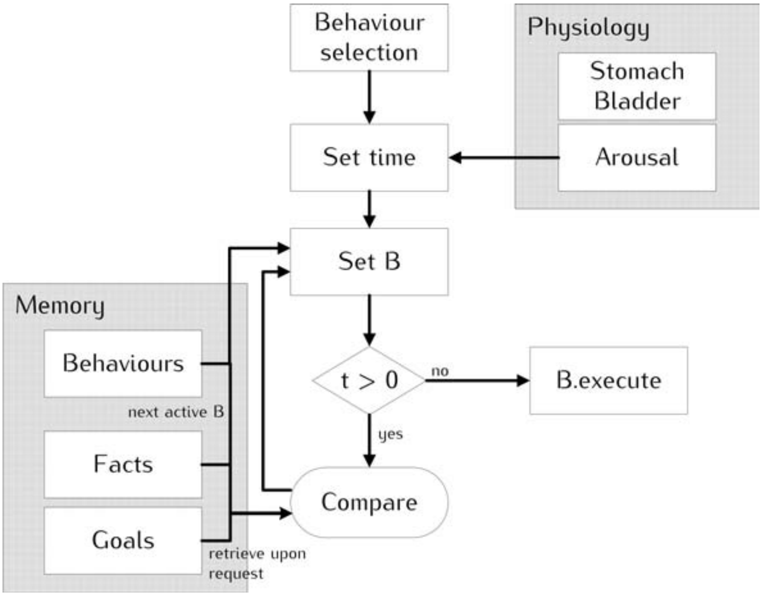

Figure 3.6: The behaviour selection process that compares the potential behaviour options within a restricted amount of time.

in this way, a more detailed description can be given of several notions in psychology, such as norm saliency, automatic versus deliberate processing, or the cognitive styles of repetition, imitation, deliberation or social comparison (Jager, 2000). The effect of arousal can be described as causing automatic processing at cost of deliberate, reasoned processing. It is considered to be automatic, as the increase in 'time-pressure' affects the selection of one of the most activated behaviours. Lower time-pressure can be related to reasoned processing enabling the comparison of multiple behaviours. Another relationship can be identified concerning the direction of the more abstract cognitive style description of repetition, imitation, deliberation and social comparison (Jager, 2000). Repetition and imitation are related to high time pressure with respectively a dominant identity goal and social goal. These two cognitive styles also match the expectation that a focus on oneself makes it more likely that behaviour will be repeated, as the last behaviour exhibited will still be highly activated. A focus on the social environment will convey a highly activated group norm, resulting in a higher probability to imitate. This thought is also consistent with the thought on norms that was expressed earlier, stating that norms, when salient, are strong determinants of behaviour. In short, arousal affects the time an individual has for the decision-making process, for comparing and selecting suitable behaviour.

Comparison: within the time available, a behaviour will be selected based on the behavioural options, goal dominance and behaviour expectation. The behavioural options are the behaviour rules residing in memory. As mentioned before, the behaviour rules in memory are ordered in accordance with their activation level. This activation level changes due to perception. The behaviour that is most active will be the first one to be used for the comparison, then the second, etc. The comparison of two behaviours involves the extent to which each behaviour is expected to satisfy the goals. The expectation of a particular behaviour (behaviour fact) together with the dominance of the goals, allows for a preference of a particular behaviour over the other. For example, when the social goal is dominant, walking towards other people is more 'optimal' than walking away from people. In a situation where safety is dominant, the optimality would shift to walking away. The role of situatedness and dynamics are fully incorporated here.

In short, to be able to choose a certain action or to sense the internal and external world, the functional part of an individual will perceive, interpret and be motivated to act according to a certain internal/external situation. To be able to do so, reference was made explicitly to several basic components that allow an individual to exhibit behaviour: physiology and memory as well as the processes of perception and behaviour selection. Perception and behaviour selection are the link with the outside world, affecting and using the internal state. Physiology gives rise to perceptual restraints and to a bodily state that affects perception and behaviour selection. Memory allows an individual to store knowledge about behaviour giving rise to a certain mental state.

3.4 Translating context into the cognitive level

To describe the behaviour of an individual in a crowd, all the ingredients have now been selected, both the relevant external influence factors and the internal world factors. In this section context will be included in the CROSS model by translating the environmental influence factors into the cognitive level that affects individual behaviour in a crowd context. Here, *translation* means specification at the functional level. On the one hand, the way an influence factor is represented will be described and, on the one hand, the influence path will be explained. The factors from the physical as well as the social environment will be discussed below.

3.4.1 Physical environment and the cognitive level

For an individual to live in a physical world, he must be able to be affected by the world he is situated in. In other words, there must be an internal representation of environmental factors, such as physical objects. In the festival context, scenario-specific physical objects, such as a stage, bar, toilet, walls, certain areas and other people, are part of the environment that need to be known. These objects are represented as facts in memory of an individual, ensuring that an individual is able to recognise a bar when he sees one. In addition to being able to identify the objects that surround him, the individual is also affected by them. Physiology is affected by the intake of food which fills the stomach, by going to the toilet which empties the bladder, and the perception of density which is related to the arousal level. Memory is updated in terms of goal satisfaction: standing close to the stage affects the identity goal, whereas density is related to satisfying the safety goal.

Density

In this thesis, *density* was identified as a relevant physical influence factor. Only density that is perceived locally can affect an individual (see section 3.2). On the basis of research that relates density and behaviour, it was deemed necessary to incorporate both a physiological and a psychological influence (see section 3.1.1). Density affects behaviour through the internal state of an individual. In the studies on density, three types of influence relationships can be distinguished: 1) density affecting physiology; 2) density affecting psychology; and 3) the indirect effect of physiology and psychology on each other. To explain the role of density, a description of all three relationships is needed. The third relationship concerns an interplay that requires an understanding of the role of the effects on both physiology and psychology. For the sake of simplicity, this study will be limited to the incorporation of the first two relationships.

In the first relationship, arousal[19] is assumed to be affected by density. The link between external stimuli and arousal has been coined *the mere exposure effect* (Zajonc, 1980; Cottrell, 1972; Sanders, Baron, & Moore, 1978). The mere presence of other human beings causes an increase in arousal level. The mere exposure effect has been used to explain phenomena of social facilitation and inhibition by means of the stimulating or diminishing effect on performing tasks while others are present. Although this simple relationship between external stimuli and arousal does not fully cover the phenomenon at hand, the importance of social conditions (i.e. psychology) has become very clear. Arousal is not only affected by physical presence, but also by the interpretation of this presence itself (Brown, 2000; Baron & Kerr, 2003; Hewstone & Stroebe, 2001). This concerns the third relationship type: the combination of the roles of physiology and psychology. This insight supports the view that both a physiological as well as a psychological effect should be incorporated.

The second relationship concerns the psychological relationship of density, which is related to a feeling of safety. It is simply assumed that a local rise of is related to an increased feeling unsafety[20]. This is motivated by the biological drive human beings have to remain safe. An individual is continuously alert for potential danger and has the corresponding bodily organisation for split-second action. This mechanism is organised by our autonomic nerve system, in particular by the dominance of the sympathetic nerve system that prepares an individual to deal with danger (Kalat, 2001), e.g. the 'fight/flight' mechanism (Baron & Richardson, 1994). Whether a person feels safe or unsafe due to the perception of density depends on personal attributes as well as on context. Personal differences in the way density is interpreted are quite common[21]. For example, a difference has been found between men and women. Men appear to be affected more by the restrictions of their personal space, which is related

[19] Arousal is the attentional state of an individual, a state of alertness that is low when a person is sleepy, normal while being awake under normal conditions and high in stressful or exiting situations. The latter is related to the physiological measure of the heart rate and blood pressure of a person (Kalat, 2001).

[20] There are also situations where the opposite effect can occur i.e. being part of a group can result in a increased feeling of safety, for instance, when being confronted by a rivalry group. The CROSS model can be easily refined or adapted (with theories being replaced) while the basic framework of a situated individual still reflects the core idea of human information processing system.

[21] One could add that the same person probably will show differences too from one moment to another. Within the context of this research that would go too far.

to their territorial claims (Leibman, 1970; Patterson, Mullens, & Romano, 1971). It is important to take these differences into account while theorising. However, context must not to be underestimated. A person might find a high density nice or safe during a festival, but uncomfortable or unsafe when standing on a train going home from work.

Both the role of arousal and safety perception convey the effect of density on the internal state of an individual, and thus on behaviour. However, the descriptions above concern the intentional level and must be translated to the functional and physical concepts of the CROSS model. Figure 3.7 visualises the internal representation and effect of density via the two routes: via the physiology update by affecting arousal, and via the memory update of the safety goal. This figure shows the role of density by moving from the group level to the cognitive level and back in six stages. At the group level, density may increase, but only a locally perceived increase of density will affect an individual (1). The perception of density directly affects arousal (2), i.e. when density rises, arousal will rise as well. The other effect of perception is established via a memory update of the satisfaction level of the safety goal (3). In this formulation, an increase in density will decrease the satisfaction of the safety goal. Given the preference level of a particular individual, dominance of the safety goal is derived. This dominance will affect the relevance of a certain behaviour that is used to compare the behaviours with each other. This simply means that some behaviours are more relevant in the situation in question (4). However, as a consequence of the rise of local density, the internal time to choose a behaviour will decrease. Because of this, the individual might not be able to address all behaviour options (5). Therefore, when density increases, the behaviours with the highest activation level are most likely to be chosen. After behaviour is chosen and exhibited by a number of individuals, behaviour patterns can be observed at the group level (6).

Density also has a side effect on the probability of a behaviour to be selected that is related to the concept of saliency[22]. Increased density simply indicates an increase of the amount of people that surround an individual in a crowd. More people in the surrounding of an individual leads to an increase in the amount of behaviours that are observed and thus primed, i.e. activated. A higher activation level increases the probability of exhibiting the same behaviours as one's local surroundings does, which in its turn increases the likelihood of that behaviour to be chosen.

3.4.2 Social environment and the cognitive level

For an individual to live in a social world, he must be able to distinguish between people in terms of different relationships. Being with friends or with strangers affects an individual in a different way. To be able to distinguish between people, these persons are internally represented as person facts in the individual's memory. In this thesis, the focus lies on the presence of friends and leaders representing the social environment. Like density, the influence of a friend or a leader can be translated into the cognitive level representing the effect at a functional level via memory updates

[22]Recall that saliency implies that whatever is dominant in someone's cognitive system will affect behaviour. For instance, you feel that taking care of the environment is important and you are walking in a street with a lot of garbage on the ground. If your environmental attitude is not 'activated' (salient) at that moment in time, the probability of you throwing your garbage on the ground will be greater (Cialdini, Reno, & Kallgren, 1990).

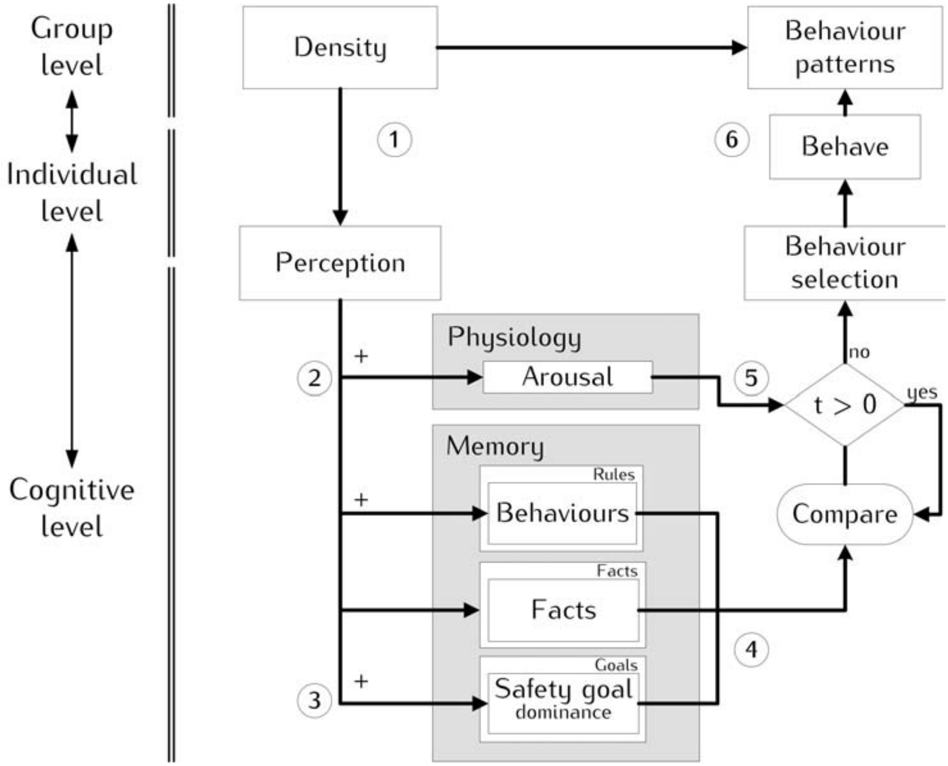

Figure 3.7: The role of density in crowd behaviour patterns at the cognitive level is described through physiology and memory update. A perception of a high density level increases the arousal level, which diminishes the time an agent has to choose his behaviour. Increased density together with a low or high safety perception makes the safety goal more or less dominant at different density levels depending on the relevance of the different behavioural options.

(perception). When an individual perceives his local environment and identifies other people, his social goal will be satisfied, especially if one or more of these people is considered to a friend or a leader. Satisfying the social goal by the presence of others is related to an individual's drive to belong to a group. Although the direct hazard of being alone is not prone, the mechanism still works, humans are group animals. The role of friends can be described in a very simple manner, it just represents the people an individual prefers to be close to when attending a festival. This is based on the fact that people attend these kinds of events together with other people in small groups of 2, 3 or 4 people (Aveni, 1977). The role of leadership is more sophisticated. A person's influence is mediated through the perception of the person who sees either the other or himself as a leader. Considering a person as a leader affects whether certain behaviour is valued as 'suitable' in a given situation, which implies that the behaviour facts (expectations) are updated.

Leadership

As indicated before, in this thesis. leadership will be dealt with as a social environment factor. Within crowds leadership represents a social influence. This is not only because leadership can often be observed in crowds, but also because it magnifies the heterogeneity of the perceived social influence in a crowd (i.e. power relationships). In the literature, the following relevant effects of the presence of a leader can be distinguished: the tendency of followers to imitate leaders, and the coordinating effect of leaders by 'giving orders'. In this thesis crowd behaviour is described from the individual perspective. With regard to the perception of a leader, a distinction can be made between perceiving oneself as a leader or perceiving someone else as a leader. Perceiving oneself as a leader can influence behaviour in terms of manipulating or coordinating others in order to reach a common or individual goal. The tendency to manipulate or coordinate others is driven by maintaining or increasing personal power or status (*power distance theory*, (Mulder, 1977)). The 'obedient' behaviour of 'followers' serves as feedback, confirming the self-perception of a leader. Unlike the usual approach where the focus lies on the leader himself[23], in this thesis the focus is placed on the 'followers' perspective, i.e. perceiving someone as a leader. The reason for this nonstandard viewpoint is that this thesis aims to increase a general understanding of crowd behaviour. Therefore, a focus on the influences on people in general is more obvious in this thesis, than a focus on a few individuals that consider themselves leaders. In accordance with this focus, the CROSS model limits itself by incorporating only the effect of perceiving another person as a leader, leaving the perception of oneself as a leader out for now. Please note that this is not a distinction between different types of individuals, but between different types of relationships, which implies that the perception changes from one person to the other.

In this thesis, perceiving someone as a leader makes the behaviour this leader shows more suitable.Some behaviour becomes more suitable as a consequence of the behaviour a leader exhibits or of suggestions provided by a leader. This influence is based on the tendency of human beings to obey someone who is perceived as an authority (Milgram, 1974; Hofling, Brotzman, Dalrymple, Graves, & Pierce, 1966). The way an individual is being influenced can be seen as both feedback that an individual receives on his own behaviour in terms of rewarding or punishment as well as following the directions indicated by this leader. In order to describe the effects of perceiving someone as a leader in the CROSS model, these effects must be translated into the functional level. Figure 3.9 shows the paths of leadership influence, moving from the group level to the individual level and vice versa in five steps. If a leader is perceived as such by an individual, this leader will be standing in the individual's range of sight (locally). Only then a leader can have an effect (1). The behaviour that a leader exhibits can be considered a form of feedback, stating that the behaviour is suitable in the social context in question. This is translated by changing an individual's expectation for this particular behaviour in satisfying the social goal, which is an update of a behaviour fact (2). The social goal dominance, together with making certain behaviour more suitable for a particular social setting, makes it more likely that the behaviour is selected and thus shown (3). Generally, after behaviour has been

[23]For instance, leadership has often been described on the basis of personal traits, skills, or the context in which a person becomes a leader.

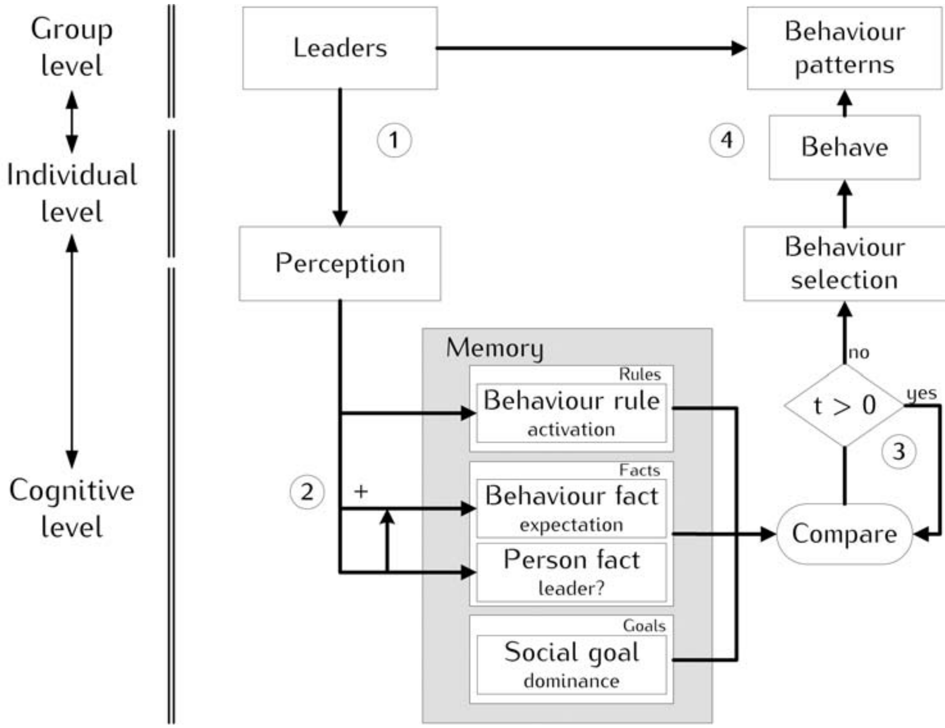

Figure 3.8: The role of leadership in crowd behaviour is described at the cognitive level via the perception (memory update) of another person as a leader. Perceiving someone as a leader increases the social goal satisfaction level as well as the expectation of the behaviour that a leader exhibits. In this way, when 'social behaviour' is more likely, this especially makes the behaviour performed by the leader more 'suitable'.

chosen, group level patterns that incorporate the role of leadership can be observed (4).

3.5 Conclusion

In this chapter the theoretical model CROSS was described. This model incorporates the multiple levels where crowd behaviour emerges (group level) and is affected (individual and cognitive level). To understand crowd behaviour patterns, it is crucial to describe and explain potentially relevant factors at the level where the actual influencing takes place. In this thesis, the influences will be specified at the cognitive level, as it is important to know *why* and *how* behaviour is chosen in order to understand this behaviour and, consequently, the behaviour patterns that emerge in crowds. It is important to take both the environment and the characteristics of an individual into account in describing and explaining behaviour. The roles of the environment and the individual have no predefined order of importance. It depends on the situation whether an internal or external factor will dominates behaviour. Context refers to the relevant physical and social factors of the environment. This thesis focuses specifically on the roles of density and leadership. The characteristics of an individual are described in terms of a situated individual who is represented as a cognitive structure with physiological and mental characteristics. A situated individual stands for an individual that is both embodied and embedded. The context and the intra-individual structure will be merged into a description of a crowd in a festival context, based on its dynamics, social situation and the individual.

Chapter 4

Simulation to Understand Crowd Behaviour

Computer-based simulation is a type of modelling or, in other words, a way of understanding the world (Gilbert & Troitzsch, 2005). Simulation introduces a way to think about and look at phenomena that is especially suitable for complex systems, i.e. a total of changing, interconnected parts that exhibit properties that are not obviously given the properties of the individual parts (emergence) (Wilson & Keil, 1999). In general, the use of simulation can have two purposes: *understanding* and *prediction*[1]. Using a simulation for understanding aims to uncover the underlying rules of behaviour patterns, whereas using a simulation for prediction aims to reproduce the dynamics of certain behaviour. Note that the underlying rules do not have to match reality, only the outcome should match reality. In this thesis, simulation will be used as a tool and method for understanding. More specifically, it will be used to gain a better understanding of the mechanisms that underlie the emergent patterns of crowd behaviour.

The behavioural dynamics of a crowd is regarded as a complex system: the multitude of factors that are of influence plus the interplay between the internal and external world of an individual, give rise to the complexity of behaviour and the behavioural patterns that can be observed. In the interaction process, behavioural patterns are the result of interactions between individuals, an emergent process (bottom-up). The patterns themselves will in turn affect the behaviour of the individuals. This downward causation is a top-down influence. The multi-level influence and the continuous dynamics give rise to a complex phenomenon where it is difficult to derive cause and effect due to the multitude of influences and their directions. In a crowd, the social environment adds an extra dimension to the complexity, because the social environment is not only different for each individual in terms of what is perceived, but also in terms of the way it is perceived, as this depends on the person and the situation. This heterogeneity and context dependency make crowds a good example of a social complex phenomenon. In the previous chapters, the importance of the

[1] A simulation can also have the purpose of entertainment. Even though they have no scientific goal, real-life games can be similar to the models that aim for understanding or prediction, as they have to be real enough for the gamer, i.e. believable.

individual level of agency in understanding crowd behaviour patterns was addressed. This has resulted in a multi-level study with the cognitive level as the level at which behaviour will be described. These multiple levels are represented by: the group level where behaviour patterns emerge; the individual level at which behaviour is exhibited; and the cognitive level to represent the individual in a crowd. A multi-level analysis (i.e. micro-macro analysis) will relate the group level patterns with the level at which behaviour is chosen and affected. The approach to relate the group and individual level is considered the way to gain better understanding of the underlying dynamics. To represent these important notions of interaction, multi-levelness and the cognitive level of description, a multi-agent simulation will be used. In this way, crowd behaviour patterns will be generated, representing a crowd as multiple computational individuals, i.e. agents, that interact.

In crowd research, like in most studies, scholars all have their own traditions in the methods they use. Crowd research is part of the social sciences where observation and experimentation are common methods to answer research questions and develop theories. These methods are limited in their ability to answer questions such as: "What gives rise to behavioural patterns in crowds?" or "How does a certain type of behaviour arise?". The explanations of traditional crowd research methods, such as observation studies, media studies and post-incident research, are limited. Media studies only focus on specific outcomes of crowd behaviour in terms of riots or emergencies. Post-incident research is similarly restricted, as it looks for answers after an incident, of course relating preceding events to the incident. Observational studies however, do not have knowledge of the outcomes like post-incident research. This results in valuable descriptions of crowds and of the kind of behaviour and behavioural patterns that are displayed, regardless of the outcomes. However, observational studies cannot answer *why* and *how* behaviour patterns arise. It is only possible to look at individuals and groups from the outside, while the internal decision-making process remains a black box. Normally, the next step would be to conduct experiments, relating relevant factors or testing a potential explanation for the why and how questions. However, it is almost impossible to perform experiments in crowds. The factors that play a role are numerous, which makes it difficult to control the circumstances and create an experimental setting. In addition, an ethical issue would arise, as the safety of the subjects cannot be guaranteed.

Computer-based simulation is a method that is not bothered by these limitations. It allows for the exploration and manipulation of each setting that is incorporated in the computational model, and is thus able to investigate the underlying mechanisms in crowd behaviour by studying the formation of behavioural patterns (see chapter 1). Therefore, in this thesis, simulation will be used to gain better understanding of a social phenomenon (Gilbert & Troitzsch, 2005), i.e. social simulation). The strengths of the following relevant fields will be combined: knowledge of human behaviour from the social sciences, knowledge of both human information processing and computational modelling from the cognitive sciences and artificial intelligence. With that, the resources are available to explore the dynamics of crowd behaviour.

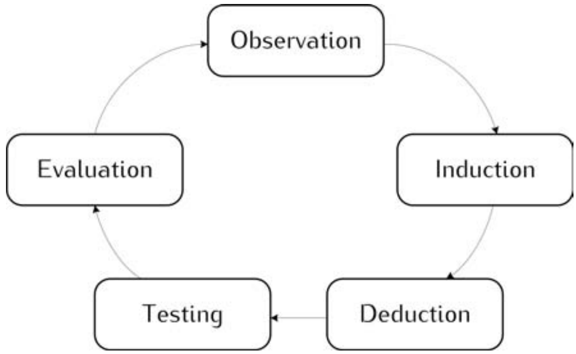

Figure 4.1: The empirical cycle of science (Groot, 1961).

4.1 The scientific cycle

Science aims to explain phenomena by systematically analysing the subject of interest. The cycle of proposing and then evaluating an explanation to come to new proposals is known as the *empirical cycle*. Figure 4.1 visualises this cycle.

All scientific studies implicitly or explicitly make use of models. "A model is a simplification - smaller, less detailed, less complex, or all of these together - of some structure or system" (Gilbert & Troitzsch, 2005, p. 2). Models, both theoretical and computational, are based on the assumption that the comparison between the input and output of the model with data from the real world will say something about the value of one's model for the real world. In figure 4.2, derived from Gilbert & Troitzsch (2005), the logic of simulation as a method is represented. The *target* represents the subject of study, for instance, a social process. Next the researcher develops a *model* and provides a description based on observations, empirical data, theory or other sources. This covers the observation, induction, and deduction steps. The model is then used to generate data in a simulation model, data will be derived in a theoretical model or data data will be predicted in a statistical model. These data can be compared to data collected by traditional methods. The comparison closes the loop and the explanatory power of the model can be assessed. Depending on the goal of the research the data do not have to be an exact match of reality to establish the explanatory power of the model. If the goal is to gain an understanding of the underlying mechanisms, reality can be different while the processes are still comparable. The evaluation of the model can be used as input to adapt the model, improving it making it more specific or broadening it.

The simulation research conducted in this thesis will follow the empirical cycle and make use of a computational model. However, the design of a computational model follows the steps of the so-called regulative cycle,which overlaps with the empirical cycle. The *regulative cycle* represents the systematic way of solving real-life problems using both a theoretical framework and models with a design-perspective that are used in engineering and computer science (Helmhout, 2006). When compared to the empirical cycle, the development of a simulation requires several additional steps which are common for the development of a simulation in an empirical domain.

These steps are incorporated in the life cycle of a simulation, visualised in figure

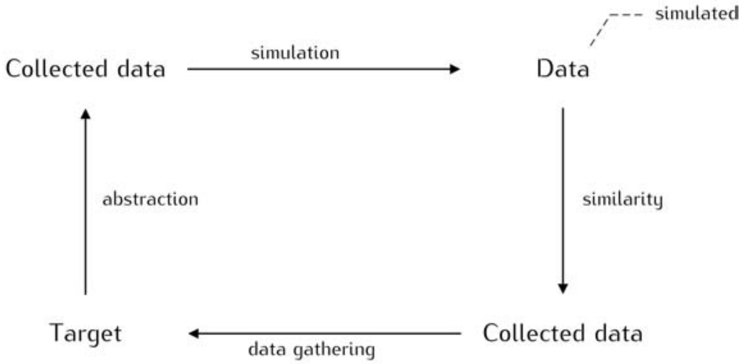

Figure 4.2: The logic of simulation as a method, derived from Gilbert & Troitzsch (2005).

4.3. The life cycle of a simulation can be divided into five phases that describe moving: 1) from the real world to a theoretical model[2] (conceptual modelling); 2) from a theoretical model to a computational model (formalising and coding); 3) from a computational model to an experimental model (experimental design); 4) towards understanding the model (experimentation); and 5) towards understanding the real world (redefinition). The transition from one phase to another always involves a verification and validation step. *Verification* involves checking whether the model represents what it is supposed to represent. For example, the theoretical model should incorporate all assumptions, whereas the computational model should not have any bugs. *Validation*, on the other hand, involves checking whether the model is a good model. A model is a good model when the descriptions of the processes in the conceptual model are theoretically or empirically sound, when the coherence is maximised (Thagard & Verbeurgt, 1998), or when the behaviour of the computational model corresponds to reality. In order to meet the objectives of the study, the model should allow to explain or predict (Law, 2007; Gilbert & Troitzsch, 2005; Balci, 1998).

4.2 How can simulation be used to understand crowd behaviour | the phases of the CROSS model

The following sections will describe the development of the CROSS simulation model of crowd behaviour for each phase. The phases involve the development of, the implementation of and the experimentation with the CROSS model. Ech phase in the simulation cycle will be described, addressing both the main decisions made with regard to the CROSS model as well as the verification and validation of the model.

[2]In computational modelling, the term conceptual model is often used. In this thesis the notion of theoretical model will be used as this fits the jargon of the social sciences better. However, both terms imply the same here.

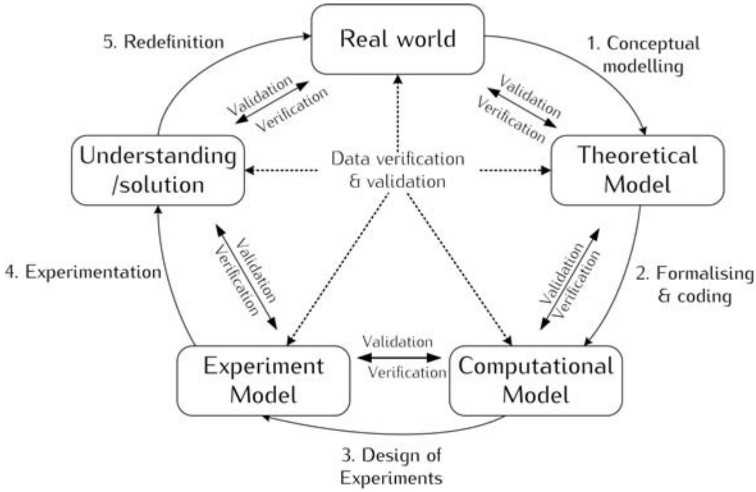

Figure 4.3: Life cycle of simulation research in an adapted version of (Balci, 1998), derived from (Helmhout, 2006).

4.2.1 Phase 1 - from the real world to a theoretical model

In the first phase, the theoretical model is developed, which corresponds to the first three chapters of this thesis. It is the phase in which "one starts by identifying a ‘puzzle’, a question whose answer is not known and which it will be the aim of the research to resolve" (Gilbert & Troitzsch, 2005, p. 18). In this thesis, the emergence of behaviour patterns was identified as the ‘puzzle’ and target of the investigation (chapter 1). In moving towards a model, current crowd research was studied, serving as a base (chapter 2). Other theories from the social and cognitive sciences were included on the base of existing knowledge of behaviour in crowds (chapter 3).

The major choices at this point evolved around the question *What to include and what to exclude?* In fact, in modelling crowd research, the latter remark "what to exclude" is very important, as there is a multitude of factors playing a role in crowd dynamics. The choices made in this thesis have been guided by the combination of the modern foundation of crowd research (section 2.1.3) and the level of detail that is considered necessary for the development of a simple yet sufficiently rich model. Crowd behaviour is generated by the individuals constituting the crowd, where their behaviour is the expression of a continuous interplay between the external and internal world. This approach results in a model that integrates different sources of influence, including the physical and social environment as well as the physiological and mental parts of the intra-individual, rather than in a model that aims at incorporating all the relevant aspects of one type of influence.

At this level, verification only involves checking whether the theory represents what it is supposed to represent. The CROSS model integrates multiple theories. It is important to verify that the different subtheories are represented in the way their developers intended to represent them. For instance, if a theory describes that perceiving high-density levels will increase the arousal level, the verification step checks whether this increase is really represented in the model.

Table 4.1: An overview of the assumptions on which the CROSS model is based. The right-hand column shows the source from which the assumption originates.

Assumption	Source
Crowd behaviour is generated by individuals	Social sciences (e.g. McPhail (1991), Adang (1998))
Crowd behaviour is situation dependent	Social sciences (e.g. Adang (1998), Reicher (2001))
Crowd behaviour is a social phenomenon	Social sciences (e.g. Couch (1968), Adang (1998), Reicher (2001))
Crowd behaviour is dynamic	Social sciences (e.g. Adang (1998))
Individuals are information processing systems (= cognitive systems)	Cognitive sciences (e.g. Newell (1990))
Individuals are situated (= embodied and embedded)	Cognitive sciences (e.g. Lindblom et al. (2002))
Behaviour is goal-directed	Cognitive sciences (e.g. Kendrick et al. (2005))

Validation, on the other hand, involves determining the correctness of the theories and assumptions underlying the model. It also involves determining whether the structure, logic and causal relationships of the model are 'reasonable' (Sargent, 2000). The CROSS model's assumptions are empirically based. From regarding behaviour in crowds as generated by the individual to incorporating the role of the social context as well as the dynamics, all are entirely based on the insights of crowd research that were obtained by systematic observation studies (chapter 2). Table 4.1 provides an overview of the relevant assumptions of the CROSS model. The influence factors and the way these factors are embedded in the structure of the individual are selected on the basis of crowd research literature and social theories concerning the effect of these influence factors on behaviour (see table 4.2). The structure representing the internal world of an individual is also based on the structures used in cognitive architectures that are empirically validated. The elements that form the model can all be justified by being either context-related or evidence-based (see table 4.3).

4.2.2 Phase 2 - from a theoretical to a computational model

The second phase represents the translation of the theoretical model into a computational model, i.e. the formalisation. There are several ways to computationally model social phenomena. For the purpose of this thesis, the CROSS model must meet several criteria to be able to represent crowd behaviour: 1) it must allow for multiple levels; 2) it must describe behaviour at the cognitive level; and 3) it must allow for the dynamics that represent the continuous interaction between individuals and their context. The phase of formalisation deals first and foremost with formalising each aspect into code.

Table 4.2: An overview of the influence factors used in the CROSS model. The right-hand column shows the source from which the factor originates.

Influence factors	**Source**
Point of interest {bar,toilet,stage}	Context related
Density	Inherent to crowds
Friends	Observation studies (e.g. Aveni (1977), Kemp et al. (2004, 2007))
Leaders	Record analysis (e.g. Arts et al. (2009))

Table 4.3: An overview of the elements in the cognitive structure that are specified in the CROSS model. The right-hand column shows the source on which the specification is based.

Cognitive structure elements	**Source**
Physiology - Architecture	
Arousal	Social sciences - Mere presence (Zajonc, 1980; Sanders et al., 1978)
Bladder & Stomach	Inherent to the festival scenario & Consequence of embodiment
Limited perception	Consequence of embodiment
Memory - Representations	
Goals {Identity,Social,Safety,Subsistence}	Social sciences - Needs (Max-Neef, 1993; Maslow, 1943)
Facts	Knowledge-based on context
Behaviour facts {walk,run,dance}	
Person facts {leader,friend}	
Rules	Knowledge-based on context
Behaviour rules {walk,run,dance}	

There are different ways to model social phenomena (Gilbert and Troitzsch (2005) give an overview). For instance, system dynamics (SD), cellular automata (CA) and multi-agent systems (MAS) are widely used approaches for the computational modelling of social phenomena. A major difference between the approaches concerns the aim of the research: prediction versus understanding. In the event of prediction, a model should produce a certain type of behaviour. The description of that behaviour does not necessarily have to be valid, as long as the outcome is. System dynamics is typically a method that is used to design models for prediction. A target system, e.g. a social phenomenon, is described as a system of equations, usually differential equations deriving a future state from a particular current state (Gilbert & Troitzsch, 2005). These models remain at the macro level. In the social sciences, and especially in this thesis, the focus usually is on *understanding*, which involves the inclusion of the valid underlying processes at the individual level for crowd research. This highlights the need for multi-level models, as both the level at which behavioural patterns emerge and the level at which behaviour is generated are involved. Both cellular automata and multi-agent systems allow for multiple levels. Cellular automata models incorporate two levels[3]. They are represented by a grid of cells, where each cell can only have a small number of states. In accordance with rules, the states of a cell can change depending on the states of the neighbouring cells. These dynamics then give rise to changing patterns. Cellular automata are useful in modelling social interaction, for instance, in the spread of gossip (Gilbert & Troitzsch, 2005) or in segregation (Schelling, 1971). The advantage of the simplicity of cellular automata is at the same time its drawback: they are not practical for a description at the functional (i.e. cognitive) level. In cellular automata behaviour rules and states must be quite simple and influences are bound to be local. As has been argued in this thesis, to achieve a richer description of the internal world as well as the inclusion of the environment, an approach is needed that allows for multiple levels (i.e. more than two) and a more complex description of behaviour. This need for interaction between a more complex world and more complex entities leads to multi-agent systems.

Multi-agent systems convey an approach that involves the design, analysis and implementation of complex adaptive software systems (Jennings, Sycara, & Wooldrigde, 1998). They are characterised by the involvement of multiple levels (> 2), more complex individuals, and agents designed to interact 'intelligently' with their environment. Multi-agent systems are systems composed of multiple interacting computing elements, known as *agents*[4]. An agent is a computer system that is capable of independent action on behalf of its user or owner (Wooldridge, 2002). There is no generally agreed definition of an agent, although many have been proposed (Franklin & Graesser, 1996). As Helmhout (2006, p. 21) puts it: "Understanding the field of MAS starts with the understanding of the agent as the main component of the system". In this thesis, a general definition of an agent will be used, adapted from Wooldrigde and Jennings (1995) by Wooldridge (2002, p. 15):

> An agent is a computer system that is *situated* in some *environment*, and that is capable of autonomous action in this environment in order to meet its design objectives.

[3]Unless this CA is build out of CA's: in that case there are more more levels.

[4]The term actor is also often used instead of agent to denote an human or agent that is (represented as) a cognitive system

Two general uses of 'agent' are distinguished by Wooldridge and Jennings (1995), namely having a *weak* or a *strong* notion of agency. The notion of agency refers to the properties of an agent, but also to the level of abstraction that is used to describe the agents. The weak notion of agency implies that an agent has the properties of autonomy, social ability, reactivity and pro-activeness. *Autonomy* refers to the behaviour of an agent that has some kind of control over its actions and internal state, without the direct intervention of human beings or others (Castelfranchi, 1995; Gazendam & Jorna, 1998). *Social ability* refers to the capability of interacting with other agents in order to satisfy its design objectives. *Reactivity* indicates that an agent perceives and responds to changes in its environment in a timely fashion. *Pro-activeness* indicates that an agent does not only respond to the environment (i.e. is reactive), but also shows goal-oriented behaviour. The other use of the term agent[5] has a more specific meaning. In addition to the properties described above, agents are conceptualised or implemented using human-like characteristics, such as mentalistic notions (i.e. representations or states), attributes, etc. These agents can be defined in more detail at the intentional or functional level (Helmhout, 2006). In this sense, the CROSS model is a strong model, as the description it provides of individual behaviour in a crowd at the functional level is more precise. The notion of agency steers the design of an agent. To distinguish between strong and weak agents, the properties and differences appear in the description of the internal world of an agent. A common method describing the mind of an agent distinguishes between perception, action and cognition, which corresponds to the CROSS model description. However, to describe an agent in a crowd context, an agent must be situated. More specifically, it must be socially situated. Carley & Newell (1994) describe what is needed to develop a social agent in what they call the 'Model Social Agent':

> The Model Social Agent has information-processing capabilities and knowledge. Agents' information-processing capabilities are goal-oriented. They control the agents's ability to handle information. Agents exist within an environment that is external to handle processing capabilities. The agents' knowledge is to an extent dictated by the external environment in which it is situated. The Model Social Agent exist in a particular situation (both physical and social). This situation is the environment perceived by the agent, but how the agent encodes it, and how much of the environment is encoded by the agent, is an open issue. The agent has a goal. The agent enters a situation with prior knowledge. The agent may have an internal mental model of the situation that differs from that held by other agents in the same situation. Throughout, we take the agent as having the typical human sensory and motor devices to sense the environment and affect the situation. (Carley & Newell, 1994, p.223)

The situated agent in the CROSS model closely matches this view. As indicated before, it is necessary for an agent to be embodied as well as embedded. The interplay with the external environment refers to the physical and social situation. Being embodied can relate to the sensory and motor devices of the body. In the CROSS model, embodiment implies limited perception, as well as not being able to

[5] Particularly in the field of artificial intelligence.

walk through walls. To be able to differentiate within and interact with the environment, the agents in the CROSS model must have a mental representation of the world and behave in a goal-oriented manner. Each agent has a unique internal state and perception of the world, which leads to heterogeneity. The description of the Model Social Agent stresses the same important points that are emphasised in the CROSS model. However, there is one major difference: Carley & Newell's (1994) aim is to understand cognition, whereas this thesis is concerned with understanding crowd behaviour. Implicitly in Carley & Newells's (1994) MSA represents a complex cognitive architecture from a cognitive sciences perspective. They start from rich complex descriptions of cognitive systems that focus on the internal world of agents, indicating what is needed in terms of knowledge and what are the limitations in terms of processes when moving to agents that must be able to show social action. The CROSS model takes a different approach, incorporating elements from the social and cognitive sciences that are necessary to understand crowd behaviour. Its approach is problem-driven (*"Which mechanisms underlie crowd behavioural patterns?"*) and does not presuppose nor need the full richness of an exhaustive cognitive architecture.

After deciding to design the computational CROSS model in accordance with a multi-agent systems perspective, the actual building could start. To support the development of an agent-based simulation, an MAS toolkit was selected for software development. A toolkit supports the building of sound models and saves development time. There are a huge number of agent-toolkits[6] available and choosing one requires a set of demands. Studies that compare toolkits, e.g. (Bitting, Carter, & Ghorbani, 2003; Shakshuki & Jun, 2004; Nikolai & Madey, 2009) support the formation of a useful list of criteria. For the CROSS model, in addition to comprising a Graphical User Interface (GUI), 2D/3D visualisation and an experimental setup, it was important that the toolkit would allow for 'heavy' or more complex agents. Furthermore, the programming should be object-oriented and in a language that is commonly used, like Java. The tool itself should contain good user support, i.e. documentation, tutorials and a community that stimulates further development by actively providing support. In addition, it is considered an enormous advantage if the toolkit has distinguished itself in the social simulation field, for instance by providing packages to define the social environment or supporting the performance of experiments. Lastly, an open source tool would be appreciated. After a rough selection primarily based on discussions with other social simulation researchers, the visualisation and available documentation resulted in four potentially suitable toolkits that were compared: Jade, Mason, Netlogo and Repast[7]. Jade, Mason and Repast appeared to be suitable to model complex agents. Netlogo did not allow for these complex agents to be modelled, but was used for preliminary versions of the CROSS model and for the exploration of several conceptual ideas. Netlogo showed strong advantages in terms of visualisation, simplicity, development speed and experimentation support. The choice between Jade, Mason and Repast was based on less crucial issues. All use a living language Java, and therefore allow object-oriented programming, which thus provides the freedom to develop any type of agent. Jade is especially suitable for distributed simulations and thus scalability, which was, however, not considered a

[6]See the survey of Nicolai and Madey (2009) for an overview .

[7]The websites of the toolkits (agent Development Toolkits: An Evaluation, ; Jade, ; Mason, ; Netlogo,) can be found in the references.

criterium for the current model. As Repast specifically contains support for behaviour models (i.e. social simulation) as well as an experimental set-up, it was decided to use Repast as it meets all the criteria.

Verification of the computational model must then ensure that both the computer programming and the implementation of the theoretical model are correct (Sargent, 2000). This includes making sure that there is no systematic behaviour that should not occur, so-called artefacts[8]. The use of Repast, or any other toolkit for that matter, makes verification easier, as the adopted parts of Repast are already verified because the verification step is part of software development. To test whether the CROSS simulation model is free of error, a pragmatic approach was chosen and scenario tests were performed. In a scenario test, the expectations of the behaviour of the computational model are tested. In this way, errors are easily identified. With regard to the CROSS model, this involved a test of the major functions: *perception* and *behaviour selection*. By testing these processes, the adequacy of the underlying functions is also tested. The perception test checks all aspects of perception over time. This involves checking whether agents situated in a certain location perceive their surroundings and are affected by it. More specifically, this test is conducted for the perception of points of interests (POIs), other agents and behaviour. In the CROSS model, the perception of a POI, e.g. the bar, toilet or stage, that is situated at a festival should result in a physiology update as well as a goal satisfaction, i.e. memory update. To perceive others, concerns updates of goals or facts, depending on whether the agent is co-audience, a friend or a leader. The perception of behaviour should result in a behaviour rule being primed. The behaviour selection test works in a similar way. Each simulation time step (i.e. tick), one agent is chosen randomly, and the chosen behaviour is then compared to the other behavioural options `{walk,run,dance}`. This comparison is based on the activation level of the chosen behaviour, which should be either higher than or equal to the activation of the behavioural options, or on the the fact that the utility is higher than the other behaviour options[9].

The validation is the most important part of this phase, as it indicates whether the simulation is a good model of the target, i.e. crowd behaviour. The validation of the computational model involves not only the translation of each relationship and concept into a specific function or variable (formalisation), but also the overall behaviour of the computational model. The validation with regard to formalising is realised by choosing the functions or variables. These are either related to reality, i.e. derived from observation studies or case studies, or relative values that represent the theorised behaviour. The validation of the CROSS model as a whole is carried out by means of *event validity*, *comparison with other models*, and *animation*. Data validation, i.e. gathering empirical data to compare the simulation outcome with data from real world settings, will not be applied[10]. Event validity concerns the "events" occurring in the simulation model that are similar to the target events (Sargent, 2000). During a festival, typical events include people going to the toilet, bar or moving towards the stage. These can also be observed in the simulation, see the screen captions

[8]For example, at one point, the agents repeatedly formed a diagonal across the screen. Apparently, the calculation of the heading of the agents did not work properly, which caused this strange result. This is called an artefact.

[9]For the details see the code of CROSS on openABM and SourgeForce.

[10]This does not fall within the time and topic scope of this project, but would nonetheless be a strong validation technique.

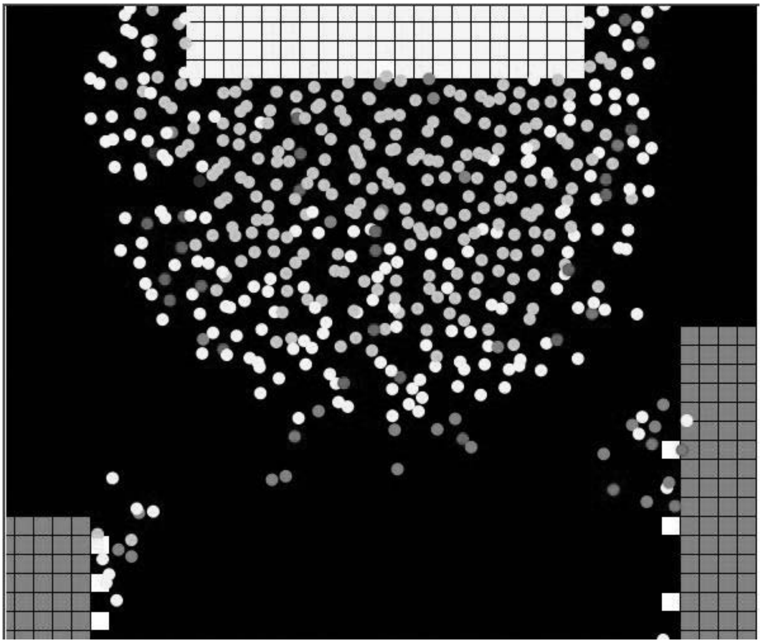

Figure 4.4: A screen capture of the CROSS model in a festival scenario, visualising the typical arc pattern around a stage.

of the simulation in figures 4.4, 4.5 and 4.6. In addition, people at a festival go to the bar together, which will be shown in the simulation as well. The validation technique of the comparison to other models is related to other simulations that are in itself validated (Sargent, 2000; Law, 2007). The CROSS model can be compared to other models based on movement patterns (e.g. arcs, rings, lanes) that are simulated and validated by using empirical data (Helbing, Buzna, Johansson, & Werner, 2005) and observation studies (Tucker, Schweingruber, & McPhail, 1999).

These key observations of patterns in a crowd (i.e. arcs, rings, companion clusters, and lanes) can be related to the notion of 'stylised facts' that is used in economics [11]. The last part of the validation at this level concerns animation. The operational behaviour of a model is displayed graphically as the model changes over time (Sargent, 2000). Not only is this an effective way to find invalid model assumptions but also to enhance the credibility of a simulation model (Law, 2007).

In addition to the usual tests of verification and validation, this phase also involves a sensitivity analysis. Sensitivity analysis gives an impression of the sensitivity of the model to changes in the parameter settings and the initial settings. Not all goals are, for instance, sensitive to the initial settings, only the subsistence goal is fully dependent on the bladder and stomach state that is set. However, also the extreme settings were explored, resulting for instance in a maximum of people that could be placed in the grid. Overall, the behaviour of the model remained stable throughout this visual inspection.

[11] A stylised fact represents the simplified presentation of an empirical finding (Kaldor, 1961).

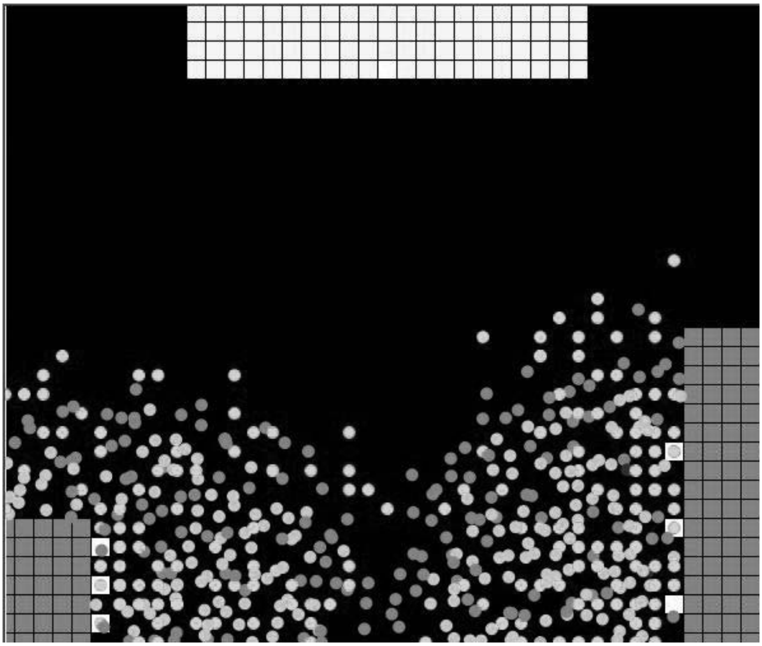

Figure 4.5: A screen capture of the CROSS model in a festival scenario, visualising the typical arc pattern around the toilets and the bar.

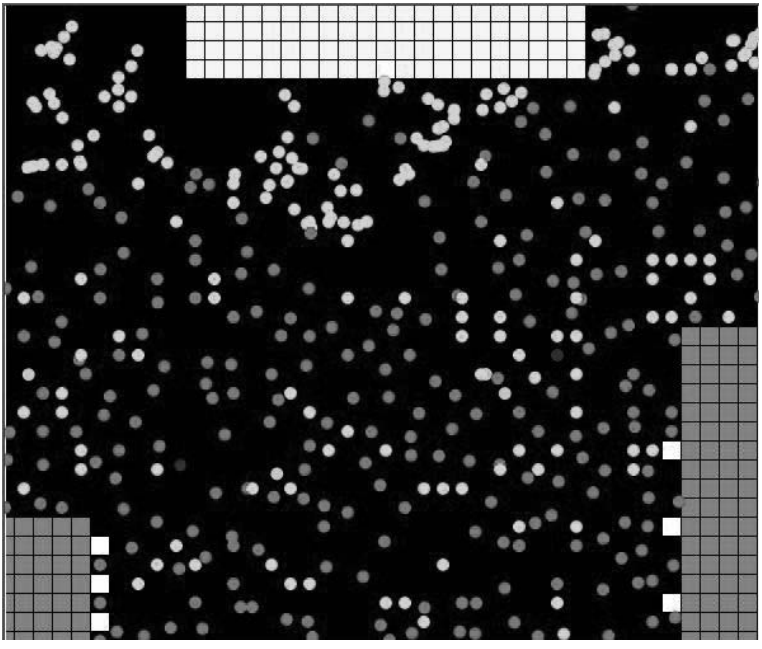

Figure 4.6: A screen capture of the CROSS model in a festival scenario, visualising the typical companion cluster patterns at the festival terrain.

4.2.3 Phase 3 - from a computational to an experimental model

Phase 3 prepares the computational model for experimental usage, i.e. the experimental design. The variables for experimentation are specified and the simulation is adapted in such a way that the relevant input settings can be assigned and that the output variables are written into an output file. Special attention will be paid to the output measure at the group level, and to relating the group level to the underlying levels. The CROSS model has been built around the main aim to gain a better general understanding of crowd behaviour by understanding the behavioural patterns. The research question: *"Which mechanisms underlie crowd behaviour patterns?"* and the role of the physical and social context in behaviour drive the two experiments that will be discussed in this thesis (see chapter 6 and 7). What is meant by behavioural crowd patterns? As discussed in chapter 1, behavioural patterns are patterns of movement, e.g. arcs, rings, lanes, companion clusters (see figure 1.1), but they also include patterns of clusters of people performing similar behaviour, e.g. dancing, talking, drinking. In this thesis, *behaviour clustering* is used as an output measure. Behaviour clustering describes the behavioural pattern of identifiable subgroups of agents exhibiting the same behaviour at a particular moment in time. It is difficult to define a group measure because what is it that defines the boundary of a group? Therefore, the choice was made to define a group on the basis of the behaviour that is shown and the distance between agents. At a dyadic level, agents are 'connected' in that sense. The more overlapping dyadic connections, the larger the group. Behaviour clustering will capture the overall behavioural characteristics by indicating the amount or size of the identifiable subgroups in a number. It is an aggregate notion of what the agents do (i.e. individual level → group level)[12]. At the group level, statistical analyses (ANOVA) will be conducted to check the effect of a manipulation. In addition to the classical design of an experiment at one level of description and the use of statistical analysis to find causality, the understanding and explanation is sought by relating the group level to the individual level, i.e. the micro-to-macro emergence (Sawyer, 2003). To be able to explore this relationship, so-called *life histories* will be used. They are represented by the behaviour and internal states of the individual agents. Life histories show the internal dynamics and state of an agent and provide insight into *why* and *how* a certain behaviour is chosen.

Verification of the experimental model concerns a test to see whether the additional experimental settings are set correctly and whether the output is written correctly into an output file. This is an obvious functionality to prevent false causalities or explanations.

Validation concerns the choices made in the manipulation of the experiment. The experiments conducted with the CROSS model concern density and leadership, which will be discussed in chapter 6 and 7. In the density experiment, the levels of density are varied as well as the way density is perceived by the individual in a crowd. In the leadership experiment, the percentage of individuals in a crowd that is regarded as a leader is varied. The choices in the manipulation of the experiments are given in table 4.4. The table indicates that the selected levels of density relate to reality. However, the other choices are based on the interest in exploration driven by the hypotheses.

[12] Behaviour clustering is formalised as the amount of dyads that show the same behaviour at the same time-step, while being in the physical vicinity of each other (see the (pseudo) algorithm 6.2 in chapter 6).

Table 4.4: An overview of the independent variables used for experimenting with the CROSS model. The right-hand column shows the reasoning behind the choice of the manipulation. Details concerning these variables and experiments are discussed in chapters 6 and 7.

Experiment manipulation	Source
Density levels {low,medium,high}	Estimation, Safety management guidelelines (e.g. Fruin (1971), Weidmann (1993)
Safety perception distribution {low,medium,high}	Choice of exploration with the assumption of normality
Leader ratio {0,10,25,100}	Choice of exploration

4.2.4 Phase 4 - from experimental model to understanding the real world

In the fourth phase, the CROSS model is used to explore the research questions by actually conducting the experiments. To be able to run the experiments, several decisions must be made concerning the duration of a run and the amount of runs. There is no rule of thumb for the duration of a simulation that would adequately reflect an event of about five hours. The duration should just be long enough to generate a sufficient amount of information about the behaviour of the model. There are models that reach a kind of equilibrium indicating an endstate. However, the CROSS model does not intend to reach such a point, as there are continuous dynamics. To decide on a cut-off point in terms of the length of a simulation run, the simulation was run with several different durations (`50, 100, 1000 and 5000` ticks) in order to compare the outcome of behaviour clustering. Figure 4.7 clearly demonstrates that `50 ticks` does not provide sufficient information about the general behaviour of the model. There appears to be an onset effect that is negligible when looking at the runs of a duration `>1000 ticks`. Therefore it was decided to use a `runlength` of `1000 ticks` as this would incorporate sufficient richness in information to describe the behaviour of the model. A simulation with `5000 ticks` did not seem to contribute to more understanding, but would just take more time to run the experiments.

The number of runs represents the iterations (i.e. repeated experiments) that are needed to distinguish whether the outcome of a manipulation is relying on chance or not. In the experiments described in this thesis, the number of runs is set to `30`. The significant results of the experiments justifies the number of repetitions (see chapters 6 and 7).

Verification of this phase involves a check on whether all the initial settings of the manipulations are correctly set.

Validation in this phase would concern the actual link with the real world and is realised by exploring the behaviour of the model. There are three ways of comparing the model and the real world according to Sargent (2000): 1) graphs of the model and system behaviour data, 2) confidence intervals, and 3) hypothesis testing. In this thesis graphs and hypothesis testing are used in which another level of explanation is

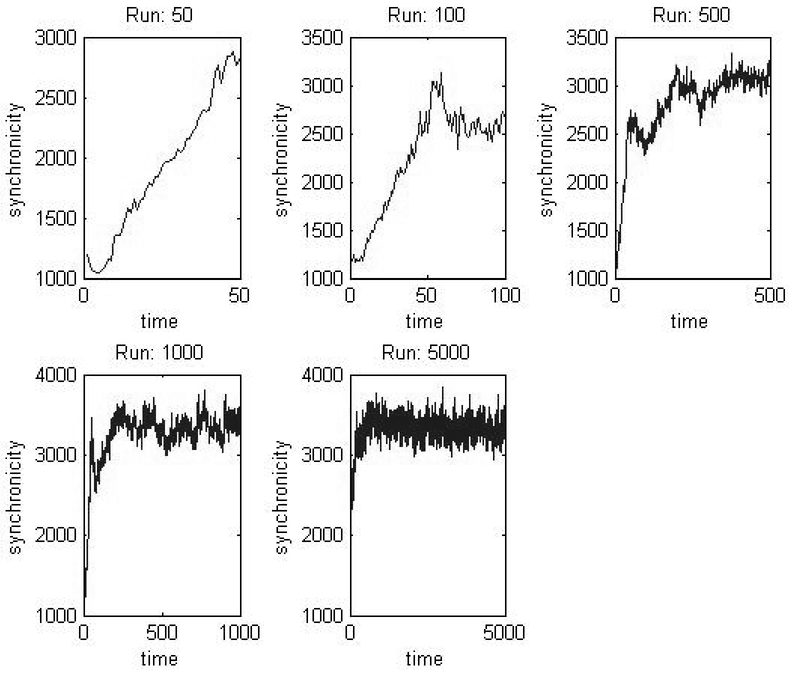

Figure 4.7: The visualisation of the output for various simulation run lengths.

added by using the life histories.

4.3 Conclusion

In this chapter simulation was described as a tool for understanding crowd behaviour. By addressing the four phases a simulation must go through, the choices and justification were made explicit. In developing a theoretical model (phase 1), assumptions and influence factors of the CROSS model discussed in Chapter 3 were summarised and linked to their theoretical and/or empirical foundations. In the development of the computational model (phase 2) the choice for a multi-agent system approach in order to model crowd behaviour was discussed. This choice was made in accordance with the requirements that the design of a multi-level model of a crowd composed of situated agents must satisfy. To be able to use the model for experiments (phase 4), the adaptations of the model for the density and leadership experiments were described in terms of the specifications and the choice for output measures and initial settings. It is good practice to *verify* and *validate* (V&V) before moving on to the next phase, hence every phase involves V&V.

As the first phase (i.e. from the real world to a theoretical model) has already been discussed in the preceding chapters, the remainder of this thesis will deal with phases 2, 3 and 4, i.e. the description and use of the computational model.

Chapter 5

The CROSS Model - A Computational Crowd Model

In this chapter, the computational modelling phase will be described (phase 2). This comprises a step in which theories and ideas will be transformed and translated into variables and formulas, i.e. formalisation. Section 4.2 described the multi-agent design as being the most suitable given the requirements of the CROSS model: 1) multi-levelness; 2) behaviour description at the cognitive level; and 3) interplay between individuals and their physical and social context. While agent-based modelling is a common approach in modelling crowd behaviour (see table 5.1), a rich description of the individual in a crowd at the functional level has been rarely found in crowd behaviour simulations. Such an extended internal description is important, as it allows for answering and exploring the *why* and *how* questions. The computational model is the result of a process of formalisation. Formalisation is an important phase, as computational models forces one to be concrete and specific where most theories and ideas are not. The computational model is realised as crowd simulation by implementation in Java and by use of the MAS toolkit Repast.

The multi-disciplinary approach that was taken in developing the theoretical model will also be adopted in the computational model. Before commencing the translation of the theoretical model, existing simulation models were studied to see whether they were wholly or partly suitable for use in the computational model.

5.1 Existing crowd models

Crowd behaviour simulations exist since the late seventies. The recent overview of current crowd research, provided by Challenger et al. (2009c) explicitly includes several learning points on the current state of crowd simulation (Challenger, Clegg, & Robinson, 2009a), the following in particular:

1. Real-time systematic observations and expert knowledge are vital to the development of a realistic simulation model. They form the foundation of the assumptions (e.g. typical crowd behaviour, direction of movement) and also provide data for validation.

2. The most realistic simulation tools are populated by intelligent, autonomous agents, capable of making independent decisions and reacting to environmental conditions.

3. Most simulation tools are not based sufficiently on research literature.

4. Future simulation tools should aim to include:

    (a) Groups of people within a crowd.

    (b) Emotions of individuals.

    (c) Interface between people and traffic.

These learning points fit the approach taken for the CROSS model. The CROSS model is based on current knowledge gained from recent literature and observations in crowd research. Consequently, crowd behaviour is modelled by describing behaviour at the individual level using agents. A CROSS agent is sensitive to its physical and social environment, whereas its internal state gives rise to the behaviour it shows. As the focus is on behavioural patterns, this thesis also includes groups within a crowd. Although emotions are not modelled as such, certain cognitive states could be linked to emotions, e.g. an agent that walks away from a crowded area because the safety goal is dominant could be considered being afraid. The last point, i.e. interaction between people and traffic, can be interpreted in a broader sense as the need to include the interaction between people and the environment, which is achieved in this thesis.

Challenger et al. (2009c) tend to focus on the practical performance of the tools of crowd simulation, e.g. computational power, believable agents and practical training needs. In this thesis, the focus is on the explanatory or descriptive power of crowd simulation. The crowd behaviour simulations that are used most frequently in practice usually involve movement of pedestrians. They are used to gain an understanding of not only the way people walk in designed spaces (Therakomen, 2001), but also the way people move during an evacuation (Still, 2000; Helbing, Farkas, & Vicsek, 2000). In addition to pedestrian movement a strong focus lies on riot situations (Granovetter, 1978; Feinberg & Johnson, 1988; Jager, Popping, & van de Sande, 2001; Epstein, 2002; Patten & Arboleda-Flórez, 2004; Mosler & Schwarz, 2005). Other simulations concentrate on specific patterns of crowd behaviour, such as consensus(Johnson & Feinberg, 1977), conformity (Tarnow, 1996) or crowd tipping (Silverman, Johns, Weaver, O'Brien, & Silverman, 2002). Table 5.1 provides an overview of several crowd simulation models. This overview does not aim to be complete, but highlights the main representatives of computational crowd behaviour models. The major differences between these models concern the purpose and the use of their simulations, i.e. to display a methodology, to reproduce a specific type of crowd behaviour or to gain a better understanding of crowd behaviour, as is the case in this thesis.

Table 5.1: A comparison between several simulations of crowd behaviour. They can be distinguished from each other by the following elements: level of description (individual level or not); the incorporation of context (physical and/or social); the inclusion of the description the internal world of an individual (physical, intentional and/or functional level); the focus of the simulation (understanding, reproducing or as a methodological study); and the behaviour described in the simulation.

Crowd behaviour	**Agent =**	**Context**		Cognition			**Focus**	**Behaviour**
simulation	**Individual**	Physical	Social	Physical	Intentional	Functional		
Johnsson (1977)	+	-	+	-	-	-	Understanding	Consensus
Granovetter (1978) Threshold model	+	-	-	-	+	-	Methodology	Collective behaviour riot
Feinberg (1988)	+	-	+	-	-	-	Understanding	Role agitators on consensus
Tarnow (1996) Phase model	+	+	+	-	-	-	Understanding	Group conformity & violence
Tucker (1999)	+	+	-	-	-	-	Reproduce	Arc & ring patterns
Still (2000) Legion	+	+	+	+	-	-	Reproduce	Emergent behaviour
Therakomen (2001) Mouse.class	+	+	+	+	+	-	Understanding	Movement in urban space
Jager (2001)	+	+	+	+	+	-	Understanding	Cluster, fight, approach-avoidance
Musse (1997)	+	+	+	-	+	-	Reproduce	Group inter-relation, collision avoidance
Epstein (2002)	+	+	+	+	-	-	Methodology	Civil violence
Silverman (2002) Game theoretic agents	+	+	+	+	+	-	Methodology	Crowd tipping
Patten (2004) Epidemic theory	-	-	+	-	-	-	Reproduce	Group violence
Helbing (2005) Social forces model	+	+	+	-	-	-	Reproduce	Pedestrian movement, Evacuation
Mosler (2005) PAX model	+	-	+	+	+	-	Understanding	Escalation processes
Nguyen (2005) Cognitive crowd model	-	+	+	-	+	-	Reproduce	Interaction civilians-military
Fridman (2009)	+	+	+	+	-	+	Reproduce	Pedestrian movement, social comparison
Wijermans (2011) CROSS model	+	+	+	+	-	+	Understanding	Behaviour dynamics

The models that focus on methodology either demonstrate show the explanatory power of simulation or explain what level of detail is required to develop realistic simulations. The work of Granovetter (1978) is an excellent example of the explanatory power of simulation. In his study, Granovetter makes sociological/psychological theory explicit (e.g. norms) and he illustrates the causal influence of individual variation within an interacting group. In addition, Granovetter is setting an example in terms of being transparent about what the model does and does not do. Epstein (2002) uses a similar approach and demonstrates how simulation can be used to understand the complex dynamics of civil violence. The work of Silverman (2002) supports the development of a tool to reproduce realistic crowd behaviour. In this study, Silverman interestingly integrates theories on human behaviour into a cognitive framework to produce human-like behaviour in a simulation.

Models that focus on reproducing outcomes of crowd behaviour do not necessarily require a realistic description. Nevertheless, including relevant factors based on current knowledge/literature on crowd behaviour can be considered a way to add realism to the simulation outcome. In the models of Musse and Thalmann (2001), Helbing et al.(2005), and Still (2000) this is clearly shown by addressing the role of the social context in models of crowd behaviour. Tucker et al. (1999), on the other hand, provide an empirical validation for the simulation of the basic movement patterns in crowds. Nguyen et al. (2005) takes an innovative approach by incorporating groups within a crowd. However, to reduce computation time, Nguyen eliminates the individual level at which behaviour is generated. The way in which Fridman and Kaminka (2009) model crowd behaviour stands out, as they translate social theory into a cognitive architecture (SOAR). Most models use simple rules and then add the relevant elements. Fridman and Kaminka, however, start from a highly detailed model of cognition by adding social elements. In this thesis, merging social and cognitive theories is considered crucial. Unfortunately, Fridman and Kaminka's model is not grounded very well in the field of crowd research. It gives the impression of formalising the myth of uniformity by relating similarity in behaviour in crowds to the formation of homogeneous groups.

The models that aim for an understanding of crowd behaviour differ from each other. For instance, Johnson(1977) and Feinberg (1988) model consensus from a viewpoint that relates to the myth of suggestibility. Although current insights imply that their assumptions are outdated, their work should be placed in its own time, as they incorporated the knowledge that was available back then. Furthermore, they used the simulation tool adequately by testing as well as reporting about these tests. Tarnow (1996), on the other hand, seems to ignore the body of knowledge available at the time and describes crowd behaviour (i.e. conformity and violence) in terms of fluid dynamics (i.e. fluid phases). The analogy with fluids comes across as an arbitrary link between the physical and the social world. However, the main objection lies in the fact that the assumptions and relationships of his model are based on Le Bon's group mind myths. The other modern models that are developed with the aim of understanding are theoretically and empirically based. They distinguish themselves by providing a description of the internal world of an individual. For instance, Jager (2001) provides a simple description of clustering and approach-avoidance, yet specifically focuses on providing an explanation that involves the interplay between the external and internal world of an individual. Therakomen (2001) also shows this broadness in integrating elements from both the external and the internal world, in this case, to understand the role of urban space in crowd movement. Mosler (2005) describes escalation processes between civilians and the military, providing a more refined description of internal processes. These last three models are in line with the view taken in this thesis. To understand crowd behaviour, a richer description at the intra-individual level is required.

The models that replicate behaviour are capable of generating realistic and valid movement patterns. These reactive models are based on boid/flocking-like rules (Reynolds, 1987), building on the knowledge available at the time in order to develop behaviour rules. Their design is, however, not suitable for answering the *'why'* and *'how'* questions.

The overview of a selection of existing models positions the approach chosen in this thesis, plus it provides a further rationale for the choices made. An agent-based approach is adopted by most models. In addition, it has also become clear that the aim is understanding which justifies the inclusion of the intra-individual level. Nonetheless, the overview of models shows the difficulty of formalising theory and limiting oneself to a minimal set of theories. In crowd behaviour, a wide diversity of behaviour and influences play a role. Therefore, a framework that allows for multiple behaviours and influences is needed to gain a general understanding of crowd behaviour. Based on these criteria, the existing models are either too simplistic to represent general crowd behaviour, they focus too specifically on a certain type of behaviour, or they do not incorporate the modern foundation of crowd research. It was therefore not possible to use any of the existing models for this study. The criteria justify the choices that were made, i.e. to stress the incorporation of both the physical and social context as well as the rich description of the internal world (i.e. cognition) of an individual. In this respect, the interplay between these factors is considered more important than including all potentially relevant factors.

5.2 Computational crowd model

The formalisation of the theoretical model described in chapter 3 allows for the exploration of crowd dynamics by running simulation experiments with the CROSS model. Multi-agent systems allow for the formalisation of the theoretical CROSS model, as all requirements can be incorporated, namely the multiple levels, a cognitive level of description and the dynamics of crowd behaviour (see chapter 4). A new computational model was developed, as existing simulation models did not reflect the CROSS model (see previous section).

The CROSS model represents a situated crowd (see figure 5.1). In computation terms a world is built that contains both the physical environment in which the agents 'live' as well as the agents themselves. In the remainder of this chapter, the formalisation of the environment and the agents will be described by specifying the concepts and relationships of the theoretical CROSS model.

5.2.1 Environment formalisation

The environment describes all objects that are not agents. It represents the physical space, such as the terrain an agent is able to stand on and move on. But it also

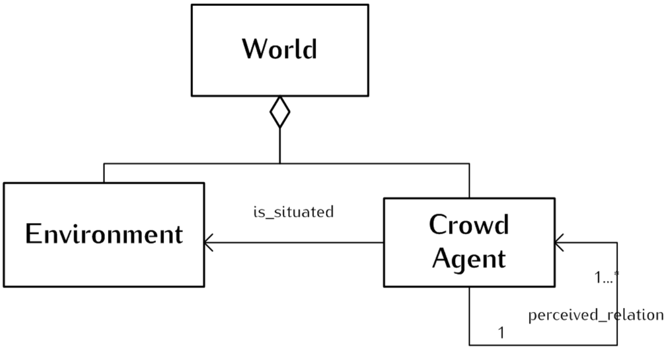

Figure 5.1: Conceptual overview of the CROSS model.

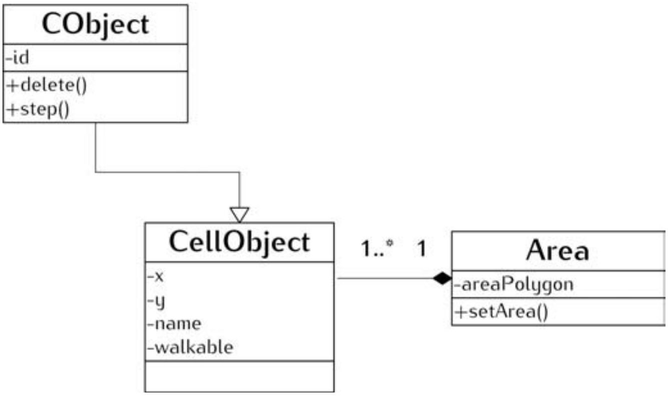

Figure 5.2: Class diagram of the environment, that is represented by cells that are walkable or non-walkable. An area indicates a set of cells that share properties (walkable (bar, toilet or stage)).

represents the objects that are relevant for a festival context, such as a bar, toilets, and a stage. In this way, the agents can distinguish between walkable and non-walkable areas on the festival terrain, or between specific objects that may fulfil the agents' goals, e.g. listening to music near the stage, having something to eat or drink at the bar, or going to the toilet (see the following section on agent formalisation).

In the CROSS model, a terrain of $256m^2$ is represented by a a grid layer representing the relevant areas (i.e. collections of cells), such as the bar, stage, toilets, or terrain that is walkable ($210m^2$ walkable terrain) or non-walkable[1]. Figure 5.2 shows the class diagram of the environment.

[1]Movement of agents is not represented on a grid space, but on a continuous layer that allows for movement within a cell or for a cell to be partly occupied. It is computationally cheaper to represent the physical areas on a grid layer and to have Repast provide the relationship between the 'movement' layer and the grid layer.

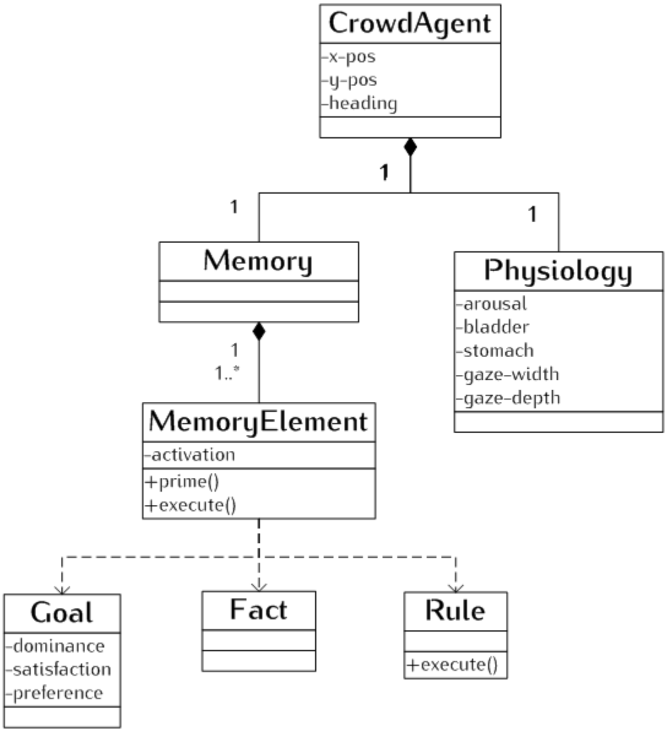

Figure 5.3: Class diagram of a crowd agent. The structure comprises physiology and a memory. The latter consists of three memory elements, i.e. goals, facts and rules.

5.2.2 Agent formalisation

The largest part of the CROSS model concerns agents. An agent represents a computational individual in a crowd that has some properties and sensitivities towards itself and its environment that give rise to the behaviour it will display. As described in chapter 3 an agent is situated (embodied and embedded). The structure of a cognitive architecture is adopted involving physiology (architecture) and memory (internal representation) to represent the internal state of an agent. The content of physiology and memory is based on the context of a crowd. Embodiment shapes the description of physiology by the incorporation of limited perception, arousal, bladder and a stomach. Embeddedness allows an agent to recognise, to interpret and to be affected by the environment which is represented as knowledge in memory, for instance recognising a friend or a social setting. Figure 5.3 shows the class diagram of the general structure of an agent.

Architecture | pysiology

Architecture represents the structure of cognition, i.e. the physical properties of the human body (embodiment) and also the notions that represent the physiological state

Table 5.2: An overview of the architecture variables.

Architecture variables			
Variable	description	range	type
Gaze width	width of sight	180 deg	CONST
Gaze depth	Depth of sight	0.8	CONST
Body size	Area an agent occupies	40x40cm	CONST
Arousal	Level of attention	[0,1]	DOUBLE
Bladder	Level of fullness	[0,1]	DOUBLE
Stomach	Level of fullness	[0,1]	DOUBLE

of the agent (arousal, stomach and a bladder). Each notion is translated into a variable concerning the physiology of the agent.

Having a body is reflected in the constraints in perception, movement and information processing that are relevant in a crowd context. This incorporates notions of limited perception (`gaze-width` and `gaze-depth`) and area occupation (body area). Perception is restricted by defining a `gaze-width` and `gaze-depth`. The default `gaze-width` of sight is set to `180` degrees, as an individual can see what is in front of him. The `gaze-depth` is set to `0.8` meter, which restricts the perception of the local surroundings an agent can be affected by to two people standing behind each other. The global perception of elements in the physical environment, for instance, the stage, bar and toilets is hard coded, which means that the agent knows where these places are. It is recognised that, in reality, individuals can perceive more than just their local surroundings, but for the purpose of this study the focus is restricted to the local surroundings. The following implementation involves an agent occupying space. This is important, not only to be able to incorporate the role of density, but also to add a crucial element of realism, as a person simply cannot walk right through another person. The dimensions of an individual are based on the average proportions of a person, i.e. 30x50 cm, which is implemented as 40x40 cm as squares are computationally cheaper to work with (Still, 2000; Haak & van der Burgh, 1994).

The physiological state, i.e. the variables `arousal`, `bladder`, and `stomach` are represented as a range varying between 0 and 1. For arousal, the range varies from a low to a high state of attention. Stomach and bladder are represented in terms of how full they are. Table 5.2 shows an overview of these architecture variables.

Representations | memory

Representations enable an individual to live in a complex and dynamic world. The knowledge that is required to understand and act in the world an agent lives in is stored in one of the memory elements: *goals*, *facts*, and *rules*. A memory element always has an activation value. The meaning and effect of this activation value depends on the type of memory element (goal, fact or rule). In the theoretical CROSS model, this abstract structure is described. It must be refined for an individual in a crowd at a festival by specifying goal, fact and rule content. An overview of this structure is provided in the class diagram of a crowd agent in figure 5.4.

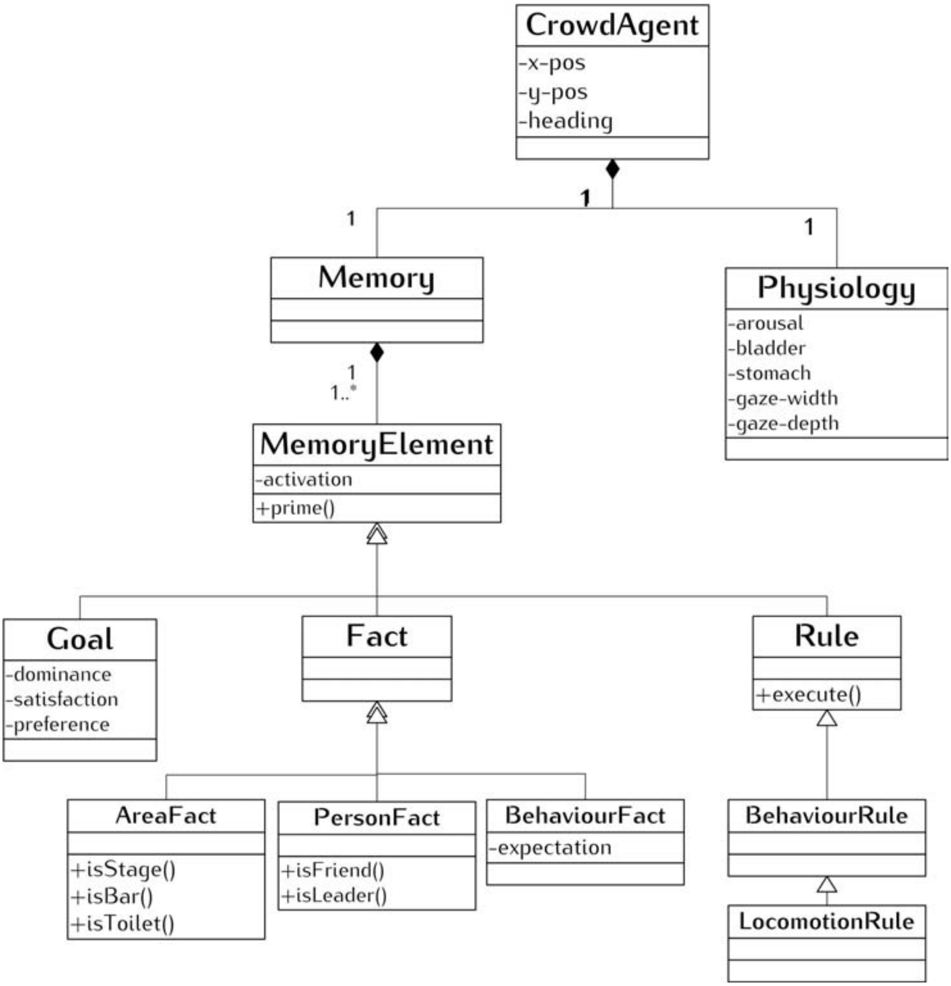

Figure 5.4: Class diagram of a crowd agent with the full memory structure.

Goals The first type of memory element is goal. A goal represents an agent's desired state. Four goals can be distinguished: *subsistence*, *safety*, *social* and *identity*. Respectively, they represent the desire a) to preserve energy, b) to remain safe , c) to belong to a group, and lastly, d) to enjoy the festival individually. As mentioned earlier, each memory element has an activation value. For goals, the activation value represents the dominance ($goalDom$) of that goal (g), as shown in equation 5.1. Dominance is the discrepancy between the desired (PREF_g) and the current (Satis_g) level of satisfaction.

$$\text{goalDom}_g = \text{PREF}_g - \text{Satis}_g \tag{5.1}$$

The level of satisfaction (Satis_g) will change over time, on the basis of what is perceived. The preferred level of satisfaction (PREF_g) is fixed, and represents an attribute of an agent. For example, an agent with a high preference level for the safety goal

Table 5.3: The goal instantiations in the CROSS model.

Goals	description
Identity	Need to be an unique individual
Social	Need to belong to group
Safety	Need to remain safe
Subsistence	Need to preserve energy
General properties	value: satisfaction - dominance range: [0,1] type:DOUBLE

can be seen as someone who is more easily scared. An overview of the goals in the CROSS model is given in table 5.3.

Facts A fact is defined as a unit of declarative or factual knowledge (a so-called chunk). Memory stores the knowledge that an agent needs to interpret perception, or to compare various kinds of behaviour. Three types of facts can be distinguished: area facts, person facts, and behaviour facts. All facts allow a person to recognise points of interests (stage, bar, toilet), other people (friend, leader), or the behaviour someone exhibits. In addition to allowing recognition of behaviour, behaviour facts convey expectations of the extent to which a particular behaviour satisfies an agent's goals. An overview of the facts in the CROSS model is provided in table 5.4.

Table 5.4: The facts defined in the CROSS model.

Facts	description	
AreaFact	recognise a stage, bar, toilet (x,y)	CONST
PersonFact	identify friend, leader {true,false}	CONST
BehaviourFact	expectation to walk, run, dance {expID,expSoc,expSaf,expSub}	CONST
General properties	activation: range: type:	retrieve time [-inf,inf] DOUBLE

The activation for this type of chunk is related to the time it takes to retrieve a fact from memory. This implies that facts with a high activation level are easily retrievable, i.e. they appear rapidly. In this way, one could also include forgetting, by disabling facts below a certain threshold from being retrieved. The activation (A_i) of a behaviour rule (i) is represented by equation 5.2. This equation is a neuron activation equation that increases the activation of the memory elements that are primed and thus become more probable or relevant for the agent at that moment(Anderson, 2007). It fits the view that what is active or dominant in the cognitive system will affect behaviour, think of the concept of saliency. The activation equation consists of two parts, the base-level activation (B_i) and the associative activation (the $W_j S_{ji}$ values). To represent the activation (A_i), only the base-level activation B_i is specified. Activation represents a measure for the relevance in a given situation, i.e. the history of element usage. Anderson (Anderson, 2007, p110.) puts it as follows: "The base-level learning activation equation specifies how the pattern of past occurrences of an item predicts the need to retrieve it." In this equation, t_k is the time since the kth practice of an item. To implement this activation function, a computational efficient approximation function for B_i is used, see then equation 5.3 (Petrov, 2006). This function generates the typical base-level activation dynamics: a sharp peak directly after usage, decay in absence of use, and gradual accretion with regular use (Petrov, 2006). It is more efficient than the original activation function, as it does not need to register every usage of the memory element. Only the last k-times when the memory element was used is stored. Index i allows for finding the stored time step (t_i) of history element usage. Time step t_n corresponds with the time a memory element started to exist, whereas n represents the total number of uses.

$$A_i = B_i + \sum_{j \in C} W_j S_{ji} \tag{5.2}$$

$$B \approx \ln \left[\sum_{i=1}^{k} \frac{1}{\sqrt{t_i}} + \frac{2(n-k)}{\sqrt{t_n + \sqrt{t_k}}} \right] \tag{5.3}$$

Rules | behaviour The last type of memory element are rules. Rules refer to the internal representations of an action, which is called procedural knowledge. In the CROSS model, behaviour rules concern motor action. *A behaviour rule* allows an agent to exhibit specific behaviour in as far as this behaviour is known. For the sake of simplicity, relevant behaviour of an agent in a crowd has been restricted to `walking`, `running`, and `dancing`. All three types of behaviour concern *locomotion rules*, as they describe the spatial movement of the agent. The activation value of a behaviour rule differs from the dominance connotation of goals and from the retrieval time of facts. For behaviour rules, the activation value gives rise to a hierarchy in the behaviour an agent knows and is thus able to exhibit. The higher the activation, the more likely the behaviour will be chosen. The changes in activation over time result in a dynamic ordering of behaviour. The activation value of a rule is similar to the facts described in activation equation 5.2. However, the way activation is used is different. For a fact, usage concerns the retrieval time, but for a rule, it concerns the order in which behaviour will be selected for execution. An overview of the behaviour rules in the CROSS model is given in table 5.5[2].

Processes | perception and behaviour selection

The dynamic element of the CROSS model is the continuous interaction of an agent with its environment via two processes: *perception* and *behaviour selection*. Figure

[2]There is only a minor difference between walking and running, as it can be deemed to reflect speeding up in optically reasonable terms.

Table 5.5: The rules in the CROSS model.

Behaviour Rules	description	
Walk	movement in space - v = 0.4 m/tick	
Run	movement in space - v = 0.48 m/tick	
Dance	movement on the spot - occupation shift	
General properties	activation:	dynamical ordering
	range:	$[-\inf, \inf]$
	type:	DOUBLE

5.5 shows this continuous loop of perception that changes the internal state of an individual (`perceive()`) as well as the behaviour selection that uses the internal state to choose a behaviour (`behaviourSel()`).

Perception Perception describes the changes in the agent's internal state as a result of the external and internal setting at a particular moment. In the CROSS model, perception is 'hard-coded', which means that there is no intelligent algorithm behind perception. Instead, the lines of influence described in section 3.3.3, *priming*, *physiology update* and *memory update*, are formalised. Perception starts with retrieving information from the world that is visible to an agent (`getInfo()`). Depending on what is perceived, the corresponding internal representation is made more active (`prime()`). This is followed by the specific update of physiology (`updatePhysiology()`), and of memory elements, i.e. goals (`updateGoals()`) and facts (`updateFacts()`). This sequence of functions involving perception is visualised in figure 5.6.

The `getInfo()`-function retrieves the environment information for each particular agent, while taking the constraints on perception into account. This environment information includes both other agents that are visible to the agent and their behaviour, and the local density. Next the corresponding internal representations of the visible persons and behaviour are primed. Priming implies an increase in the activation of a memory element in accordance with the activation function described in equation 5.2. Algorithm 5.1 illustrates, in pseudo code, the use of the activation function. The function calculates the approximation of the base-level activation of a memory element, as in equation 5.3.

Every time a memory element is used, the time is stored in `primeTimes`. In accordance with approximation function 5.3, this only requires storing the last k-times of usage instead of all the times an element was used[3]. The base-level activation is calculated based on the number of times the element is used (`timesUsed`), on the duration of existence of the element (`lifeSpan`), and on the time of usage since the kth use (`useSpan`).

The *physiology update* is conducted by setting the arousal, stomach and bladder levels. *Arousal* is represented by a threshold function that relates density to a state of alertness. Algorithm 5.2 specifies the threshold function that describes an increase in arousal when density increases. The choice for these numbers is related to the fact

[3] $K = 1$, Petrov (2006) indicates that this already works quite well.

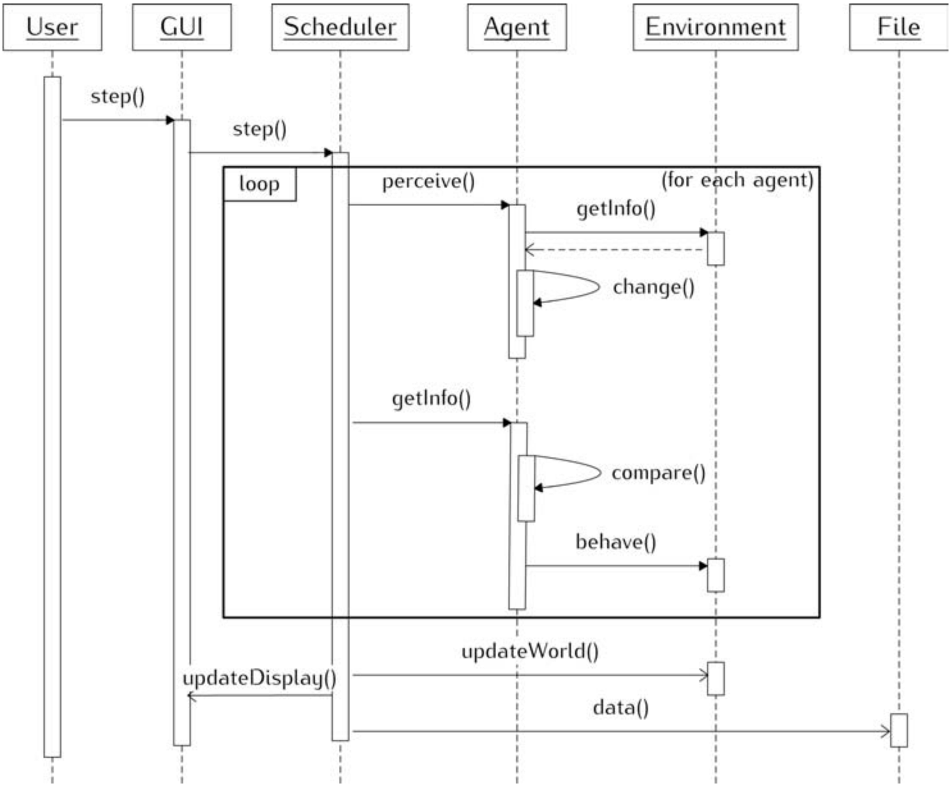

Figure 5.5: Time sequence diagram of processes in the CROSS model.

that as soon as density imposes restrictions on the freedom of movement, an increasing effect on arousal occurs. The relationship between locally perceived density and arousal is represented in a simplistic way, using a relative scale between zero and one. The lower boundary (zero) will never be reached in this scenario, as every agent is assumed to be awake. The upper boundary (1) is related to the point where density is at such a high level that 1) it is not relevant for the scope of this thesis and 2) differentiation in arousal is not needed, as the arousal level, due to the extreme pressure, would be so high that it is reasonable to assume a maximum state of awareness.

The bladder and stomach represents 'fullness' following a linear function. A bladder will increase in fullness unless emptied via a toilet visit, whereas the stomach functions in the opposite way, becoming increasingly empty unless filled by having a drink or something to eat. Regarding the pseudo-code for bladder (algorithm 5.3) and stomach (algorithm 5.4), one can see they concern a very simplistic function that causes an agent go to the bar or toilet motivated by an internal drive. This choice was made purely on the basis of context, because at a festival people drink and go to the toilet. This is driven by physiological goals. However, also social goals are involved in exhibiting this behaviour.

Memory update represents the change in the content of memory elements caused by external and internal perception. It concerns an update of the goals (i.e. satisfying

Algorithm 5.1: Pseudo-code for priming. The activation level is based on the times of usage, an an approximation function for the baselevel activation see equation 5.3.

```
currentTime = getTick();
primeTimes.addFirst(currentTime); //FIFO (first in - first out principle)
++timesUsed;
lifeSpan = currentTime − tFirstUse;
forall primeTimes do
|   useSpan = currentTime − primeTimes.last(); bsum
|   += ln( 1/sqrt(primeTimes[i]) + 2(timesUsed−1)/(sqrt(lifespan+sqrt(useSpan))) );
end
```

$$+= \ln\left(\frac{1}{\sqrt{primeTimes[i]}} + \frac{2(timesUsed-1)}{\sqrt{lifespan+\sqrt{useSpan}}}\right);$$

Algorithm 5.2: Formalisation of arousal. A threshold function related to the density level observed by an agent.

```
if density < 3 then
|   arousal = 0.3;
end
else if density > 10 then
|   arousal = 1;
end
else
|   arousal = density / 10;
end
```

Algorithm 5.3: Formalisation of the bladder - a linear function related to time - in the course of 1000 ticks an agent will probably need to go to the toilet based on the physiological urge

```
if toiletVisit == true then
|   bladder = 0;
end
else
|   bladder + = 0.0010; // after 1000 ticks the bladder is full
end
```

Algorithm 5.4: Formalisation of the stomach - a linear function related to time - during 1000 ticks an agent will need to go to the bar based on the physiological urge

```
if barVisit == true then
|   stomach = 1;
end
else
|   stomach − = 0.0010; // after 1000 ticks the stomach is empty
end
```

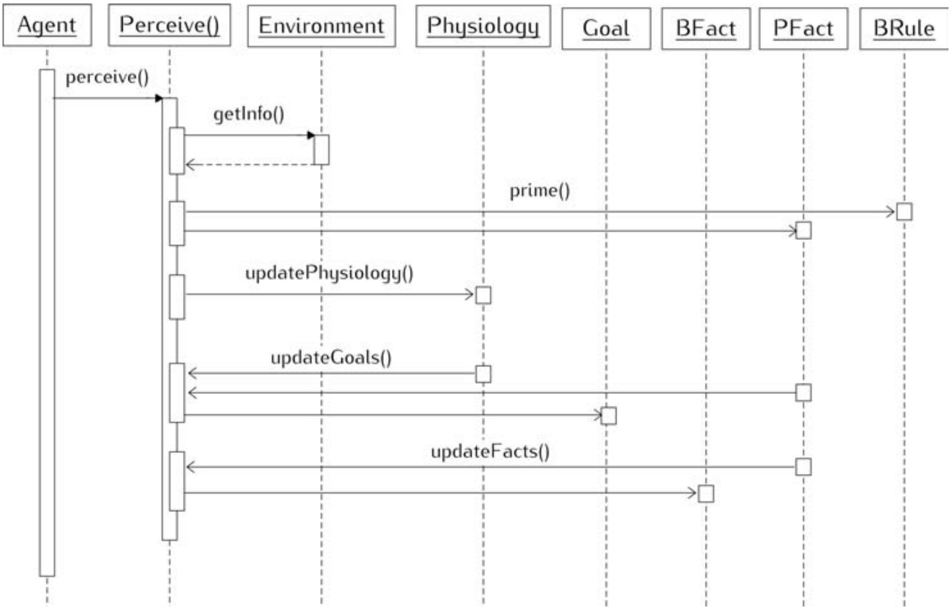

Figure 5.6: Time sequence diagram of an agent's perception.

them more or satisfying them less) and of the expectations in behaviour facts, making a certain type of behaviour more or less suitable in a particular context. Each goal has its own relationships and when satisfaction changes, all these relations will be defined depending on context-related knowledge or assumptions. The subsistence goal is directly related to the physiological state. Therefore, the satisfaction of this goal takes over the most prominent physiological urge, bladder or stomach, (see algorithm 5.5).

The safety goal is related to the subjective perception of density (see section 3.1.1). The formalisation of the safety goal represents the simple assumption of feeling unsafe when standing in crowded areas or areas that are perceived to be crowded[4]. The subjectivity of density perception depends on whether the satisfaction level is considered low or high, based on the preference of the agent. Locally perceived density will affect each agent's safety goal in the same way. However, the preference for safety, which is a heterogeneous attribute, makes the effect subjective and unique for each agent. The effect of local density is described using a sigmoid function, which is a smooth step-function represented by equation 5.4.

$$\text{Safety}(d) = 1 - \frac{1}{1 + \exp^{((-12\text{d}/\text{maxD})-6)}} \tag{5.4}$$

The social goal represents the need to belong to a group. In a festival setting, satisfaction is related to staying close to others, preferably friends. The satisfaction of

[4]It is, of course, acknowledged that being in a large group or standing close together can also increase the feeling of safety. This may, for instance, be the case for young males who show 'spontaneous' aggressive behaviour without an external interaction trigger, as was discussed Adang's initiation-escalation model (section 2.2.3). This is, however, not addressed here.

the social goal is formalised as a threshold function related to the number of agents or friends nearby. This is shown in algorithm 5.6.

The identity goal is related to the distance to the stage,i.e. being closer to the stage increases satisfaction. It concerns listening to music, the visibility of the artist, i.e. the individual enjoyment of the festival[5]. The function to describe this distance-related satisfaction is a threshold function, which is represented in algorithm 5.7

Setting the right increases and decreases of variables (or values) amounts mainly to parameter twisting, meaning that both the fluctuation of behaviour as well as the setting within the vicinity of the stage need to be optically reasonable. Therefore, the simulation was run in several different settings to see whether or not the agents would behave in the desired fashion. For instance, the arc pattern around the stage should be around the stage and should not be occupying the whole festival terrain. This implies that someone near the toilets should not be satisfied about the distance from the stage, unless the preference for this goal is really low of course.

In addition to the goals, the memory update also involves the update of behaviour facts. A behaviour fact is updated as a consequence of perceiving a leader exhibit a behaviour. The perception of a leader increases the expectation of this behaviour satisfying the social goal. The formalisation involves a rise in this specific expectation, but a decay to the default value when no leader is perceived showing this behaviour. This makes socially more desired behaviour merely a temporary effect (see the algorithm 5.8).

Perception is thus achieved via a sequence of methods that retrieves information, primes memory elements and updates physiology, goals and facts. The process is visualised in the time sequence diagram in figure 5.6.

Behaviour selection Behaviour selection is the other main process in the CROSS model. As described in chapter 3, behaviour selection involves a process of selecting 'optimal' behaviour within a certain amount of time. The most optimal behaviour is the behaviour that best satisfies the goal that is most dominantat a particular moment. This is the result of comparing behaviour from the agent's repertoire for as long as it has time to do so. Then a behaviour is chosen and executed. This sequence of behaviour selection is visualised in the time sequence diagram in figure 5.7.

Behaviour selection depends on time. The time an agent has to choose behaviour is implemented as a direct link between the arousal level and the internal time to compare the different behaviours with each other and to choose.

$$time = arousal * 10; \qquad (5.5)$$

In line with the amount of time an agent has available, the selection process starts by retrieving the behaviour with the highest activation level. For as long as there is time left, this behaviour is compared to the behaviour that is next in line[6]. The best behaviour option is chosen and used for further comparison. Every retrieval of memory elements takes time, which is based on its activation value. Therefore, it is easier to remember something that is salient, as it has a higher level of activation and thus fast er in retrieval time.

[5]Note that the level of satisfaction desired differs from one person to another.

[6]Remember that the behaviours are ordered according to their activation value.

Algorithm 5.5: Formalisation of the subsistence goal satisfaction - a direct link with the physiological state, in which the most prominent physiological urge defines the satisfaction of subsistence.

```
subsSatisfaction = MAX(bladder,stomach);
```

Algorithm 5.6: Formalisation of the social goal satisfaction. A threshold function in which satisfaction is related to the vicinity to friends of others.

```
if nearbyFriends == true then
|  satisfaction = 1;
end
else if nearbyOthers == true then
|  satisfaction + = 0.3;
end
else
|  satisfaction − = 0.1;
end
```

Algorithm 5.7: Formalisation of the identity goal satisfaction. A threshold function related to the distance between an agent and the stage.

```
if distance < 3 then
|  satisfaction + = 0.05;
end
else if 3 < distance < 7 then
|  satisfaction + = 0.01;
end
else if 7 < distance < 20 then
|  satisfaction − = 0.0025;
end
else
|  satisfaction − = 0.01;
end
```

Algorithm 5.8: Formalisation of the behaviour fact update. The perception of a leader's behaviour temporarily increases the expectation to satisfy the social goal of that particular behaviour.

```
forall bFacts do
|  if socExpectation ! = default then
|  |  socExpectation = default;
|  end
end
if leaderPerceived == true then
|  leader.bfact.socialExpectation = 0.4;
end
```

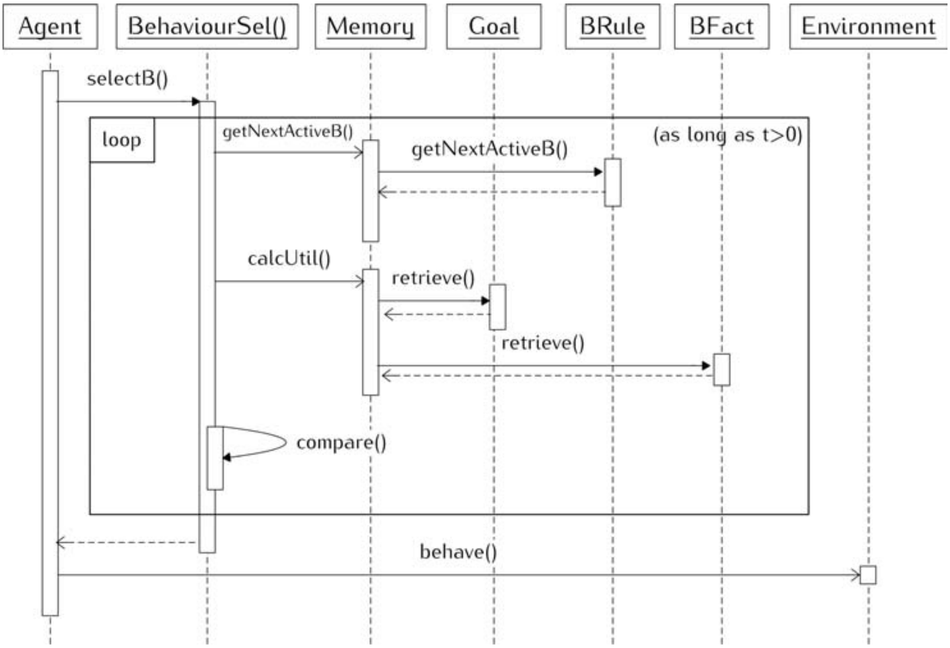

Figure 5.7: Time sequence diagram of the behaviour selection process of an agent.

Comparing behaviour Comparing behaviours to each other is represented in a function that attributes a utility value (bUtil_b) to each behaviour under comparison. The utility value represents the relevance of a certain behaviour (b) based on the agent's internal state, i.e. goal dominance, at that particular time. The comparison function is based on the expectation ($\mathrm{bExpect}_g$) of behaviour in combination with goal dominance ($\mathrm{goalDom}_g$). The expectation indicates the expected fulfilment of the corresponding goal (g) when exhibiting a certain behaviour. The comparison value incorporates the contribution of all goals in accordance with their dominance.

$$\mathrm{bUtil}_b = \sum_{g=1}^{4} \mathrm{goalDom}_g \cdot \mathrm{bExpect}_g \tag{5.6}$$

5.3 Conclusion

In this chapter, the phase of moving from the theoretical model to the computational model was described (phase 2). This formalisation phase distinguishes simulation models from other types of modelling. The formalisation phase is a creative and challenging step to make theories more concrete, precise and explicit. For each relationship and concept in the theoretical CROSS model, a computational equivalent was provided in terms of algorithms and variables. At this point, there is no room for vagueness or ambiguity, as this will not be understood by a computer. This makes the research both vulnerable and powerful. It bridges the gap between theory to a computational version, i.e. a new part is added. This translation is carried out by means of analogy, assumptions, empirical data or expert opinions. This translation can be vulnerable due to the dangers of using analogy or too many assumptions, or due to a lack of data or knowledge. The strength of simulation research lies in this new part, as the theory or idea is made explicitly. This makes it easier to detect errors, and leads to precise and powerful theories that provide rich explanations.

The current form of the CROSS model is not only a computational representation of a crowd behaviour theory but also a methodology to study crowd behaviour. To be able to answer the research question, both theory and methodology were found to be necessary steps after studying literature (see chapters 1 and 2). In this way, the CROSS model enables to explore and answer the research question. In fact, the design and formalisation of the CROSS model represents the most crucial steps towards answering the research question. With the model in place, it is now possible to apply an empirical methodology and perform experiments on crowd behaviour. As a first step in exploring crowd behaviour, two experiments were performed with the CROSS-model. These experiments will be described in the following two chapters. They do not represent a goal in themselves. The aim of the experiments is to illustrate the explanatory power of the integrative, multi-level and situated approach[7].

[7]The computational model can be found at openABM and SourceForge.

Chapter 6

The Role of Density in Crowds

The beach festival described in chapter 1 is one of many cultural events with thousands of attendees organised in the Netherlands. A bird's-eye view of the beach festival site at a random moment in time would yield a view of various groups of people. These companion groups of friends or family are clustered by similar behaviour. For example, there are clusters that pay a visit to the bar for refreshments, clusters that queue up in line for the toilets, and clusters that gather around the various stages where artists perform their show. A snapshot of the crowd taken at a different moment may provide an entirely different view. Some of the clusters with similar behaviour may have grown in size, changed in composition, or show a specific type of behaviour, including undesired behaviour, e.g. the violent interaction between the police and a group of 200 visitors).

This chapter will explore the effect of density on crowd behavioural patterns, using the CROSS simulation model as an experimental tool. How are the different density levels in crowds, which are composed of individuals with different safety preferences (i.e. subjective perception of density), related to the size, composition and amount of behavioural clusters, i.e. to the groups and/or subgroups of people exhibiting similar behaviour? Explaining the formation of crowd behavioural patterns is key to understanding crowd behaviour dynamics in both 'normal' and 'extreme' settings. Therefore, this thesis will focus on understanding the mechanisms that give rise to behavioural patterns of all kinds, instead of on a specific type of behaviour. To put it differently, the assumption is that it is the same basic mechanisms that underlie 'grabbing a beer with friends' as well as 'beating someone up together'.

Density, i.e. the number of people per m^2, is inherent to a crowd, as are the physical and psychological effects it has. In research on density in a crowd context, most attention is paid to aspects of crowd safety management. The knowledge gained from these studies reflects the physical impact on individuals at different density levels. In practice, this knowledge is used to manage high-density crowds, focusing on the prevention of deaths or bodily damage (Kemp et al., 2007, 2004). The approach taken in this thesis is different in the sense that the main interest lies in the effect of density on behaviour during non-extreme or pre-extreme settings. The focus is on the behavioural impact of density, instead of on the physical impact only. It must be noted that density has been related to behaviour in research. However, existing explanations tend to explain behaviour either in terms of physiological effects or in terms of psychological effects. The CROSS model stresses the importance of *both* the physical *and* mental state.

In this study, the exploration of density will take place in a simulated festival setting using the crowd model CROSS (see chapters 3 and 5). In the CROSS model, density is considered as an external physical factor that affects agents locally. In the model, the local perception of density is influencing agent behaviour via the changes in physiology and cognition. The agents are heterogeneous in how they are affected by density in terms of safety. They differ in their interpretation of a certain density level being safe or not. The role and interplay of external and internal factors can be explored by varying the different safety preference distributions.

6.1 The role of density

The fact that crowds and density are inherent to each other triggers questions like the following: "What is the role of density on behaviour in a crowd?" and "What role does group composition play in the perception of density, and thus in the behaviour that is displayed?". These questions are relevant for practical safety management, but also for gaining a better general understanding of crowd behavioural patterns. To explore the role of density, the CROSS model integrates relevant theories on density with a cognitive-level description of individual behaviour in a crowd. Research concerning density and crowd behaviour demonstrates that density plays an important role in crowd behaviour (see section 3.1.1). Density has a direct physical impact because of the pressure and inhibition in freedom of movement it evokes. This is the main focus in study in safety management research. Density also has a psychological effect with regard to the perception of density, which is the main focus in crowding or contagion research.

The exploration in this thesis concentrates on the combination of the physical impact and the psychological impact that density has on behaviour. The physical influence of density relates the density level to the arousal level (physiology) of an agent. However, the psychological influence of density is related to an agent's safety preference, which affects the interpretation of perceived density. Each agent perceives density locally and will have a different interpretation of density, which will, in turn affect the dominance of the safety goal (i.e. feeling safe) and thus the agent's behaviour.

Taking into account these effects of density on cognition, and the presence of density in various levels, density is expected to play an important role in the behaviour agents will exhibit and therefore also in the behaviour clusters emerging in crowds. First, it is expected that a rise in density will increase the amount of people that will exhibit the same behaviour at the same time, forming behaviour clusters. The reasoning behind this expectation is based on how an agent is affected and selects behaviour. When density rises, an agent will locally observe more people on average[1]. Due to the saliency effect, the behaviour that agents observe becomes more dominant in the cognitive system, which makes the observed behaviour more likely to be chosen. In

[1] Please recall that an increase in density (i.e. group level) does not automatically imply an increase in the density that is perceived locally an agent.

addition to the saliency effect, the probability of choosing this behaviour is also increased by the effect density has on arousal. As mentioned in chapter 3, when locally perceived density rises, the arousal level of an agent increases too. A higher arousal level entails less time to decide and thus less time to compare behaviours. Hence, it becomes more likely that the most active/dominant behaviour will be chosen. As dominance is mostly affected by what is observed, the probability of imitation and/or repetition, and thus of behaviour clustering, has increased.

In addition to the role of objective density, it is expected that the way density is interpreted by agents in a crowd will also play a contributing role to behaviour clusters. The perception of density is related to the safety preference, which is a heterogeneous attribute of a population of agents. Each agent has a preference for safety, and the goal to feel safe becomes more dominant when density rises. This will vary from one person to another, depending on the level that causes the safety goal to be dominant. The reasoning behind this expectation is that only dominant parts of the cognitive system will affect behaviour (see chapter 3). This makes certain behaviours, e.g. moving away from crowded areas, more relevant than others, e.g. dancing. Moving away from others is primarily driven by the internal need to remain safe, regardless of what other people do. Other behaviour, such as dancing or moving to the bar or the stage is more linked to the social context. A crowd that is mostly composed of agents with a high safety preference, i.e. agents who are quickly intimidated by density, will display more specific behaviour to enhance this feeling of safety and will therefore display less behaviour clusters, as the social context is less relevant. However, in a crowd composed of agents with a low safety preference, i.e. agents who are less quickly intimidated by density, the feeling of safety is not prone. In other worlds, these agents are more sensitive to the social context, which will increase behaviour clusters.

The effects that rising density and safety preference have on perception (crowd composition) are expected to interact. Density affects an agent in two ways: by way of physiology (i.e. arousal) and by way of psychology (i.e. safety preference). The combination of these two factors is expected to cause a stronger increase in behaviour clustering, when density increases and the safety preference decreases. To put it differently, a crowd with a low preference for safety will show a stronger increase in behaviour clusters when density rises than a crowd with a high preference for safety. Altogether, density is expected to be positively correlated with behaviour clustering in a crowd. It is expected that behaviour clustering increases because of the effect of density on arousal, which restricts the time available to select behaviour and therefore constraints the behavioural options. The role of safety makes certain behaviours more relevant than others. Figure 6.1 visualises these expectations, showing the generally positive relationship between an increase in behaviour clusters, density and safety preference rises. The interaction effect is illustrated by the difference in slope in each density-safety preference relationship.

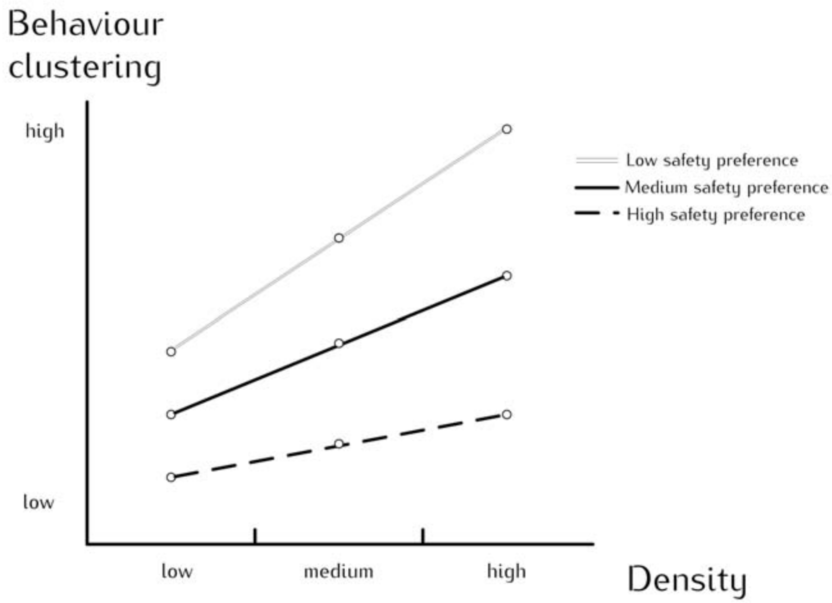

Figure 6.1: The expected relationship between density and behaviour clustering in a crowd for different levels of safety preference showing how a rise in density is expected to increase behaviour clustering, The higher the safety preference, the lower the level of behaviour clustering. The combination of an increase in density and a decrease in safety preference will interact and cause a stronger rise in behaviour clustering.

On the basis of these expectations, the following hypotheses were formulated:

Hypothesis 1: An increase in density will lead to more behaviour clustering.

Hypothesis 2: A decrease in safety preference among the agents will lead to more behaviour clustering.

Hypothesis 3: An increase in density together with a decrease in safety preference will lead to a stronger increase in behaviour clustering than when each of these factors would be taken taken separately.

6.2 The CROSS experiment model

To investigate the role of density on behaviour clustering and to test the hypotheses stated above, a 3x3 experimental design was drawn up, manipulating both density and safety preference. Density levels were varied from low to high `{low,medium,high}`, as was the safety preference distribution of agents `{low,medium,high}` safety preference. This manipulation and the resulting nine conditions are displayed in table 6.1.

Table 6.1: Design of the density experiment, showing the nine conditions resulting from the manipulation of the density level and the safety preference distribution of the agents.

Safety Preference / **Density**	Low	Medium	High
Low	Condition - 1	Condition - 2	Condition - 3
Medium	Condition - 4	Condition - 5	Condition - 6
High	Condition - 7	Condition - 8	Condition - 9

Before the density experiment can be run, the computational model must be prepared for experimental usage, i.e. phase 3 in the life cycle of simulation research (see section 4.2.3). To be able to assign adequate input settings and to store the output, the adaptation of the computational CROSS model involves specifying of the variables and adapting the simulation. The experiment variables will be further described below. The settings assigned to these experiment variables will be dealt with separately. Note that in line with the multi-level approach, variables at the group, individual and cognitive levels are defined.

6.2.1 The density experiment variables

To perform a simulation experiment with the CROSS model, the independent variables (density and safety preference) and the main dependent variable (behaviour clustering) must be specified. In addition to traditional experimental variables at the group level, this study will also define dependent variables for explanation (i.e. the so-called life histories) at the cognitive and individual levels. These life-histories will support the explanation and understanding of group level relationships, enabling the multi-level approach taken in this thesis.

The independent variables

In exploring the effect of density on crowd behaviour, two group level variables, *density* and *safety preference distribution*, can be defined. These are the independent variables. `Density` concerns the group level description of a crowd that represents the amount of people per m^2. It indicates crowdednes in three levels, namely `low`, `medium` and `high`. Note that the actual influence of density on behaviour is taking place at the individual level, i.e. local density is perceived by an agent. The local density perceived by an agent is based on the number of people within its view limited by the `heading`, `gaze-depth` and `gaze-width` at that moment. The `safety preference distribution` is the second manipulation of the density experiment. This group level variable describes the crowd composition in terms of how the overall group perceives density in relation to whether they feel safe or not. Three types of crowds will be used that have a general safety preference that is low,medium or high. High safety preference relates to a crowd in which agents tend to regard increasing levels of density as unsafe. Medium safety preference represents a crowd in which the

Algorithm 6.1: ClusterIndex (ci)
ci(agent) = $\frac{agents-in-sight}{max-agents-in-sight}$; ciMean = mean(ci(allAgents)) ;

agents feel averagely safe. Low safety preference distribution reflects a crowd with agents that will consider an increase in density less unsafe. Safety preference is an attribute at the individual level that is determined in accordance with the distribution defined at group level. Note that exploring a relationship on group level must involve a formalisation via the individual level, as this is where the actual influencing takes place (i.e. group level → individual level).

The dependent variables

Life-history variables. In explaining the group-level relationship between density and safety preference distribution and behaviour clustering, individual *life-histories* will be used. These life-histories are dependent variables for explanation, and they are measured for each agent for every time step. In the density experiment, the following individual life-history variables will be used: *cluster index*, *arousal*, *goal dominance* and *behaviour*. During a simulation run, these in-depth descriptions of an agent will be used to give a rich explanation of the group level behavioural patterns. `ClusterIndex` represents local crowdedness with regard to physical vicinity. It is measured at the individual level, and it represents a relative number, which is based on the local density of an agent (see the pseudo algorithm 6.1).

`Arousal and goal dominance` are cognitive level variables of an agent. They can be 'observed' or 'tracked' from the agents during the experiment. All values of these variables play a role in the behaviour selection process. They convey the physical and mental state of an agent at a certain point in time. `Behaviour` is the actual action that the individual agent exhibits. It is a dependent variable at the individual level that represents the outcome of the internal selection process as well as the interaction with the environment.

The group level variable. The effect of the manipulation will be captured in the dependent variable: `behaviour clustering`. Behaviour clusters represent the crowd behaviour patterns of which this study aims to lay bare the underlying mechanisms. Behavioural patterns do not only involve the typical movement patterns shown in crowds (see figure 1.1) but also the subgroups that can be identified, composed of agents behaving similarly, for instance, the group acting violently towards the LEOs in chapter 1. These subgroups vary in size and composition, but also the amount of groups in a crowd varies. Before addressing the question what the size/composition/amount could imply, the focus will lie first on the elements that affect the formation of these subgroups. In order to describe the crowd behavioural pattern of identifiable subgroups, the variable `behaviour clustering` is designed to represent the agents that exhibit the same behaviour at a given time step. Behaviour clustering thus captures the overall behavioural characteristics in one number. It is an aggregate of what the agents are doing (i.e. individual level → group

Algorithm 6.2: Pseudo code for calculating behaviour clustering

```
sumbClustering = 0;
for 0 to tickRange do
    bDyad = 0 ;
    forall tie do
        if vicinity?(tie) AND sameBehaviour?(tie) then
            ++bDyad;
        end
    end
    bClustering = bDyad / crowdsize ;
    sumbClustering += bCl12q ustering;
end
bClusterMean = sumCluster / tickRange;
```

level). Behaviour clustering is formalised as the number of dyads composed of agents that exhibit the same behaviour at the same time-step, while being in the physical vicinity of each other (see the (pseudo) algorithm 6.2).

Every connection between two agents, i.e. a tie, represents a dyad. When the two agents of a dyad are not only exhibiting the same behaviour but are also standing in each other's vicinity ($bDyad$), this contributes to behaviour clustering. Please note that when two agents are running or walking, they are considered to be exhibiting the same behaviour, if and only if they are heading in the same direction. Figure 6.2 visualises these 'rules' identifying a `bDyad`.

In figure 6.2 a), no `bDyad` can be identified, as every agent is exhibiting a different behaviour. In figure 6.2 b) and c), all seven agents show the same behaviour, yet behaviour clustering is different in the two situations. Agents who behave in the same way will cause the behaviour clustering count to increase only in as far as they are in each other's vicinity. Note that the behaviour clustering number indicates the heterogeneity or homogeneity of behaviour in a crowd. It is not designed to distinguish between the amount or size of identifiable subgroups. Figure 6.3 visualises how differently sized behaviour clusters can result in the same behaviour clustering measure.

Table 6.2 summarises the variables described that are used in this experiment to manipulate, to measure outcome and to explain crowd behaviour in the experimental set-up.

6.2.2 Model settings

Now that the experimental design has been explained, the CROSS model can be specified for experimental usage. This includes specifying every aspect of the CROSS model: the physical environment, the social environment, the experimental settings and the agents themselves. The physical environment concerns the relevant festival areas; the social environments describes the number of agents as well as the social structure and the safety preference distribution; and the agents are provided with the relevant behaviour, knowledge and sensors for the festival context.

The festival scenario was chosen because it is a suitable context for exploring

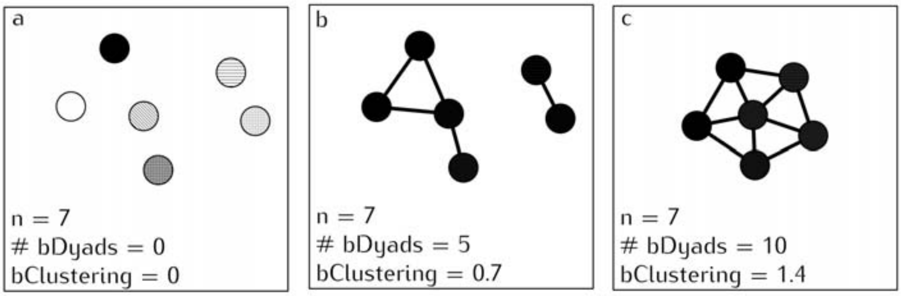

Figure 6.2: Behaviour clustering in a group represents a measure for behaviour patterns in a crowd. Behaviour clustering indicates to what extent agents that are in each others vicinity are behaving in the same way. a) shows agents that are all behaving differently (i.e. there is no behaviour clustering); b) and c) show agents that are behaving in the same way. However, their spatial locations differ and that affects physical vicinity and thus behaviour clustering.

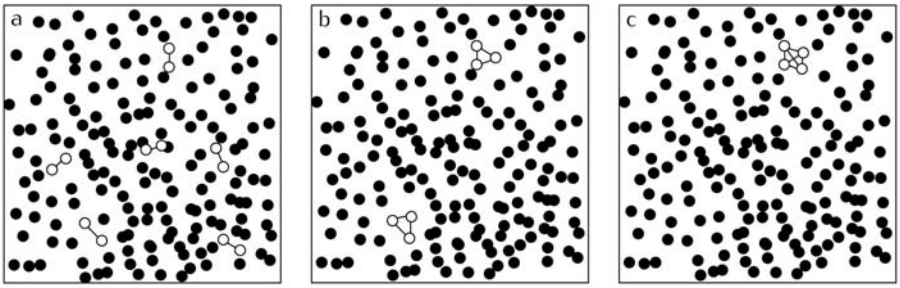

Figure 6.3: Behaviour clustering is a group level measure that represents the subgroups in a crowd in one number. This number gives a general impression of the behavioural patterns in a crowd on a scale from heterogeneous to homogeneous. The different situations that are visualised in a), b), and c) will all result in the same behaviour clustering measure, because in all three situations there are six dyads in which the same behaviour is exhibited.

Table 6.2: An overview of the variables used in the density experiment.

Density experiment variables				
Group level	Independent	Density [persons/m^2]		Low = 1 Medium = 3 High = 5.5
		Safety preference distribution [probability distribution]		Low = Beta(5,5) Medium = Beta(3,7) High = Beta(7,3)
	Dependent	Behaviour clustering		$[0, n(n-1)/2]$
Individual	Life-history	inter	Clusterindex	$[0, 1]$
			Behaviour	{walk,run,dance}
		intra	Arousal	$[0, 1]$
			Goal Dominance	$[0, 1]$

density in relation to crowd behavioural patterns. A festival context enables the exploration of the role of density in a fairly simple setting, while, at the same time, maintaining a link to a realistic crowd phenomenon. The link to a real event is, for instance, illustrated by the social structure, e.g. attending in small companion groups, or by the behaviours the agents exhibit. The availability of observations and case studies related to music events allow to establish this link by basing input setting on these observations (Kemp et al., 2004, 2007).

The physical environment

The physical environment is represented by the areas that are walkable or non-walkable. Areas are represented as a collection of grid cells. The relevant areas are defined based on the festival scenario: toilet, bar and stage areas. Each area has a point of interest that represents that area, for instance the middle part of the front of the stage is attractive for the agents when moving towards the stage. A point of interest can thus be considered hard-coded common knowledge that concerns the meaning and implication of a certain place that can be regarded as a global perception. It does not concern regular perception, which is local. This simply means that being at or near a point of interest will satisfy a goal, for instance standing close to the stage will satisfy the identity goal (see sections 3.3.3 and 5.2.2).

The social environment

The social environment is that part of the crowd model that describes the group level characteristics. For this experiment, density, safety preference distribution and the social structure are defined at the group level, where density and safety preference are specific formalisations to test the density hypotheses. Note that each group level description is translated into settings at the cognitive level, as this is the level where

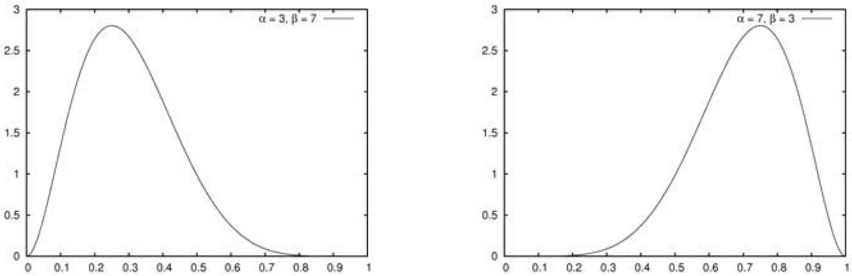

Figure 6.4: The agents' safety preference is set using a beta distribution. To represent the low safety preference distribution, the positively-skewed (beta(3,7)) distribution on the left is used. For the high safety preference distribution, the negatively-skewed (beta(7,3)) distribution on the right is used

the actual influencing takes place.

`Density` indicates the number of agents that is created for a given festival terrain ($persons/m^2$). Three levels are defined: low density (1 $person/m^2$); medium density (3 $person/m^2$); and high density (5.5 $person/m^2$). This density range is chosen to achieve different behavioural effect without moving into extreme levels. Note that the numbers are average numbers at group level. The actual influence of density takes place at the individual level. An agent will perceive the local density, which can be very different from the group level density. The levels of density correspond with the number of agents that is created, respectively 227, 681 and 1275 agents. In defining the density levels, knowledge from pedestrian movement studies (Fruin, 1971; Weidmann, 1993) was used[2].

`Safety preference distribution` is a typical scenario-related group description. Three crowd compositions are defined: with high, medium and low safety preference. The reason for this exploration is the interest in what different group compositions imply for behavioural patterns in crowds. As in real-life crowds, in music events in particular, great differences in group composition can be observed, for instance, in terms of diversity in age and gender (Kemp et al., 2007). Safety preference distribution indicates the general tendency of agents to relate density to feeling safe or unsafe. When described at the group level it is a heterogeneous attribute of the agents. For each agent, a safety preference is set in accordance with a probability distribution that captures high, medium or low safety preference, depending on the crowd composition. To specify safety preference for each agent, a beta distribution is used to approximate a positively skewed ($\alpha = 3,\ \beta = 7$), a normal ($\alpha = 5,\ \beta = 5$), or a negatively skewed ($\alpha = 7,\ \beta = 3$) distribution (see figure 6.4). These represent the low, medium and high manipulation of the safety preference distribution. The beta distribution was chosen because it is an approximation of a skewed normal distribution of which the output lies within a fixed range [0,1].

[2]With regard to the differences in these numbers, it must be taken into account that these studies focus on a relatively static situation. Not all people are moving or walking like in a metro station. This implies that higher density levels can arise, as movement takes more space than standing still.

In other words, a crowd with a high safety preference distribution is mainly composed of agents that have a safety-preference of 0.7 or higher, meaning that they will feel unsafe rather quickly. The crowd with a medium safety preference distribution serves as a control group. Most of these agents have a value around 0.5, which is average in terms of feeling safe or not. A crowd with a low safety preference distribution is mainly composed of agents with a safety preference of 0.3 or less, leading to the fact that, compared to a crowd with a high safety distribution, higher density levels are needed for a feeling of unsafety.

`Social structure` is the last group characteristic. Social structure represents the structure of the group in terms of *who knows who*. For the festival setting, social structure is reflected by the percentages of the crowd that came to the festival in pairs, triplets or quartets. People usually attend a festival together with other people, usually in groups of 2, 3 or 4 individuals. Like every group level characteristic discussed, this setting also has consequences for the individual level. At this level, companion groups are formalised in terms of the number of people that an agent regards as its friends. These relationships are reciprocal, i.e. if A is befriended with B, then B is befriended with A. In the simulation, as no empirical data are available, these groups are arbitrarily set to: 30% pairs, 30% triplets and 40% quartets.

Agents

Agents are the individuals in a crowd that 'live' in the simulated world while attending the festival. Agents generate behaviour and are affected by the situation they are in. Each agent has bodily and mental properties that need to be set. These are represented in a framework explained in detail in chapter 3 and 5.

The bodily factors that need an initial setting only concern the physiology variables of arousal, bladder and stomach. *Arousal* represents the level of attention, which is initially set at an average value (0.5). This average value indicates that the agent is in an average state of attention, i.e. it is not asleep (0) or overly excited (1). The *bladder* and *stomach* are initially set according to a beta distribution that follows an approximation of a normal distribution. For the same reasons as with the safety preference settings, a beta(5,5) distribution is used. It has the same effect as a normal distribution with the advantage that it is a discrete function with output values between [0,1]. A 'normal' distribution is used here, as there are no empirical data on which distribution approximates can be based.

The mental part of the agent is defined as a memory structure consisting of goals, facts and rules. *Goals* represent the needs that an agent strives to satisfy up to a certain preference level. The four goals (identity, social, safety and subsistence goals) must be set with an initial satisfaction value as well as a preference value (see section 3.3.2). The preference for the *identity* and the *social* goals is 'normally' distributed using a beta(5,5) distribution. The initial satisfaction value is zero for both the identity and the social goal. Zero is chosen as the default initial value, as the initial settings are not important for the future satisfaction of both goals. In addition, starting with zero as the initial value will prevent the occurrence of strange onset behaviour at t=0[3]. The *safety* goal preference, on the other hand, is distributed according to the

[3] The onset behaviour is can be called strange when the agent would act on the basis of a setting that is not affected by the context it is living in at that moment.

Table 6.3: The settings of the behaviour fact expectations. They are fixed values that represent the way a particular kind of behaviour is expected to fulfil the different goals agents have (identity, social, safety and subsistence goals). These values are used to determine what behaviour is more relevant or less relevant in a particular situation.

BehaviourFacts Expectation	**Goals** Identity	Social	Safety	Subsistence
walkExp	0.3	0.3	0.2	0.1
runExp	0.1	0.1	0.4	0.1
danceExp	0.3	0.3	0	0

safety preference distribution variation as described above. If the agent is part of a high safety preference crowd, the value is set using a negatively skewed distribution (beta(7,3)). If the agent is, however, part of a medium safety preference distributed crowd, it is represented by normal distribution (beta(5,5)). If the agent is placed in the low safety preference condition, the preference is set using a positively skewed distribution (beta(3,7))[4]. The initial satisfaction value of safety is set to `0.5`. Again this is done to rule out strange onset behaviour. The last goal is *subsistence*. The satisfaction of this goal is directly linked to physiology, i.e. the status of the bladder or stomach. The subsistence preference is set at the same value for all agents, as each agent is deemed to have a similar physiological body. The height of the subsistence preference is set to `0.8`, which is quite high. because when dominant, these basic needs can affect behaviour to a great extent.

In addition to goals, memory consists of facts and rules that each need their specific settings. *Facts* involve either behaviour or person facts. A *friend fact* is the internal representation of a friend. It is necessary for an agent to be able to recognise a fellow agent as a friend in order to distinguish which agent's vicinity is desired. A friend fact is indicated by a boolean value `{true,false}`, which is set according to the social structure defined at group level. For instance, when an agent is assigned to a pair, this means that two agents have an internal representation of each other as a friend. *Behaviour facts* are pieces of knowledge that represent the expectations of satisfying a goal when choosing this behaviour (see sections 3.3.2 and 5.2.2). This value is used to compare behaviour in terms of relevancy. The expectation values for each behaviour-goal combination are fixed values between 0 and 1, see table 6.3. The choices for the expectation values are based on the scenario. The expectation values represent to what extent behaviour contributes to the satisfaction of each of the different goals. For example, dancing is expected to satisfy the social and identity goal but not the safety goal. This is formalised by *dance* being expected to satisfy the identity goal with `0.3`, the social goal with `0.3`, the safety goal with `0.0`, and the subsistence goal with `0.0`. The behaviours *walk* and *run* are formalised in a similar way. On the basis of these values together with a dominant goal, a certain behaviour becomes more or less relevant in a particular situation. Finally, the *rules* must be specified. The

[4]The distributions are all beta distributions, as described in the previous subsection on crowd characteristics.

behaviour rules known by an agent are walking, running and dancing. Formalisation of these rules simply means that the agent is only able to exhibit behaviour it knows, and no others.

In general, the settings in memory represent the knowledge of an agent, which in this simulation, is fixed. This implies that the expectations, the number of friends and the behavioural options do not change over time. The settings determine the boundaries in terms of the number of agents and the social structure they belong to. The settings also enable agents to read information from the world they reside in, to be affected by this world, and therefore to be influenced in the behaviour they choose. An overview of the relevant settings of the CROSS model is visualised in table 6.4.

For each of the nine conditions of the density experiment, the simulation is repeated 30 times, with each run comprising 1000 ticks. For the behaviour clustering measure, the average over each run is taken, excluding the onset[5]. The life history variables are measured every tick.

[5] The average is taken over tick [100,1000] (See the pseudo-algorithm 6.2).

Table 6.4: The CROSS settings for the density experiment

CROSS - Density experiment setting								
Physical Environment	Area	toilet, bar, stage		Non-walkable, point-of-interest (x,y)s				
Social Environment	Density level	{low,medium,high} = {1.0,3.0,5.5}						
	Safety preference	{low,medium,high}						
	Social structure	Pairs	30%					
		Triplets	30%					
		Quartets	40%					
Agents	Physiology	Arousal	0.5*					
		Bladder	beta(5,5)*					
		Stomach	beta(5,5)*					
	Memory	Goal	Identity	pref	beta(5,5)			
				satis	0.0*			
			Social	pref	beta(5,5)			
				satis	0.0*			
			Safety	pref	{beta(3,7),beta(5,5),beta(7,3)}			
				satis	0.5*			
			Subsistence	pref	0.8			
				satis	Physiology-based			
		Fact	PersonFact	Friend	{true,false}			
			behaviourFact	**expectation**	id	soc	safe	subs
				walk	0.3	0.3	0.2	0.1
				run	0.1	0.1	0.4	0.1
				dance	0.3	0.3	0.0	0.0
		Rule	walk,run,dance					

*Initialisation setting

6.3 Results

This thesis focuses on laying bare the underlying mechanisms of crowd behaviour patterns. The CROSS model was designed to reflect the relevant levels of description. The precision and detail applied in describing the CROSS model will now be used to describe, relate and analyse crowd behaviour patterns from a multi-level perspective. To relate density to behaviour clustering, a relationship at group level is explored. However, in line with the CROSS model perspective, the route of explanation travels via the cognitive level. Therefore, the results of this experiment will be displayed starting from the path of influence at the cognitive and individual levels, before addressing the relationship at group level.

6.3.1 Looking under the hood – the cognitive and individual levels

Crowd behaviour patterns emerge at the individual level. Agents interact with their environment and will choose behaviour on the basis of their internal state of that moment (see chapters 3 and 5 for a detailed description). Density was explained to have two paths of influence. 1) via the perceived local density affecting arousal and increasing behaviour activation, thus increasing the likelihood of a behaviour being chosen. 2) via the perceived local density affecting feelings of unsafety (i.e. a dominant safety goal).

The effect of density starts by perceiving density locally. A rise in density at group level does not necessarily imply that all agents experience a rise in density. To illustrate this point, local crowdedness (`clusterIndex`) for `agent 1` is displayed in figure 6.5. One can see that crowdedness varies over time. With regard to the perception of local density, arousal (i.e. part of an agent's physiology) is directly affected. Figure 6.6 shows the arousal level that fluctuates due to the changes in local density. For example, the rise in clusterIndex between ticks 25-26 is directly related to the increase in arousal level between tick 25-26.

Varying density levels do not only affect physiology, they also influence the goal dominance. This is due to the fact that satisfaction of both the safety and the social goal is sensitive to the vicinity of other agents. Figure 6.7 shows the goal dominance of Agent 1's four goals over time. The fluctuation of the safety goal dominance is clearly illustrated. Both tick 25 and 30 display the safety goal as most dominant. When moving to the individual level, the agent actually exhibits behaviour that is based on its internal state at that moment, and interacts with the environment. At the same time, given the setting, the agent selects 'running' as the most relevant behaviour instead of 'walking' or 'dancing', given the current setting (see figure 6.8).

The cognitive and individual level dynamics show that the group level manipulation of density takes place via the way an agent and its internal state is affected. When moving between these levels it is important to realise that a manipulation at the group level will affect the agents differently, as each agent has its own unique environment that influences it. However, when moving back to the group level, the behaviours, including the differences, are reflected in a general effect. Figure 6.9 illustrates this difference for the clusterIndex. At the group level, the general cluster index rises between the conditions. However, the two agents visualised show that the individual local clusterIndex can deviate from the average cluster index.

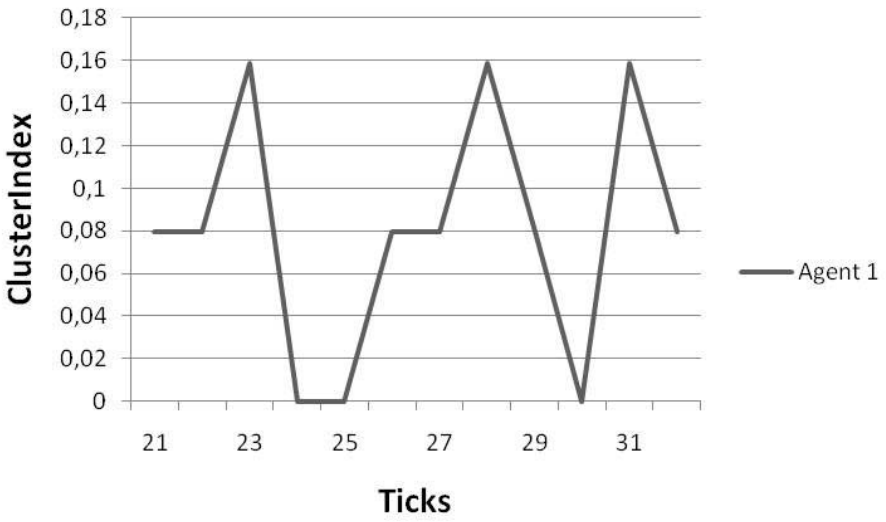

Figure 6.5: The local crowdedness that is perceived by Agent 1 between ticks 21-32. It illustrates that the environment of an agent changes, which affects what will influence Agent 1.

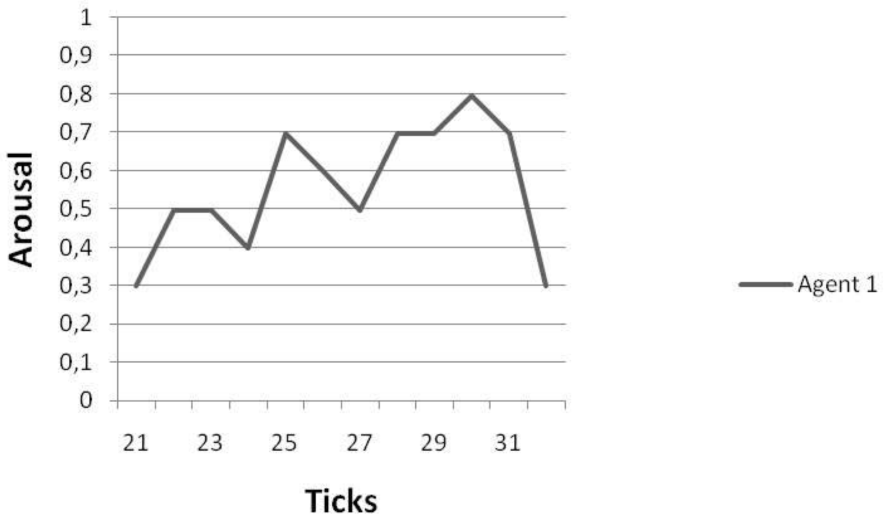

Figure 6.6: The arousal level of Agent 1 between ticks 21-32. It shows the fluctuations that are direct consequences of a changing local density [6] are shown.

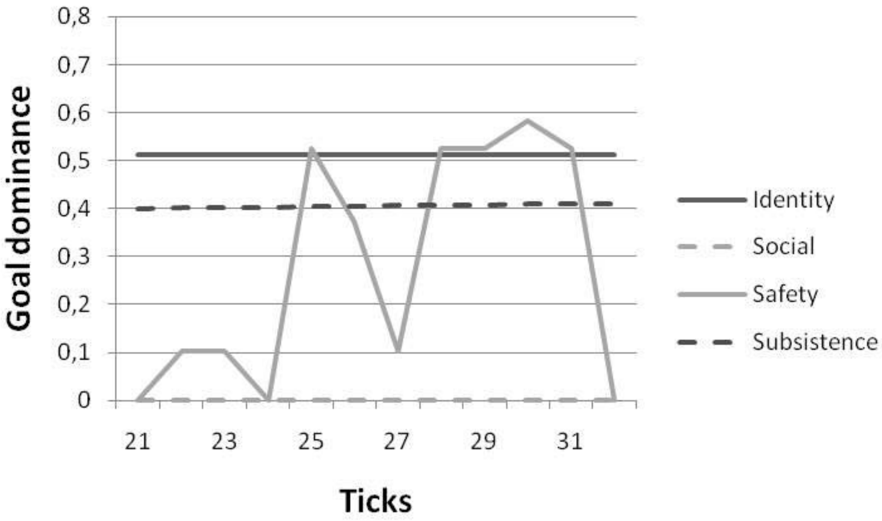

Figure 6.7: The goal dominance of the subsistence, safety, social, and identity goals of Agent 1 between ticks 21-32. The fluctuation of the safety goal dominance in particular is visible.

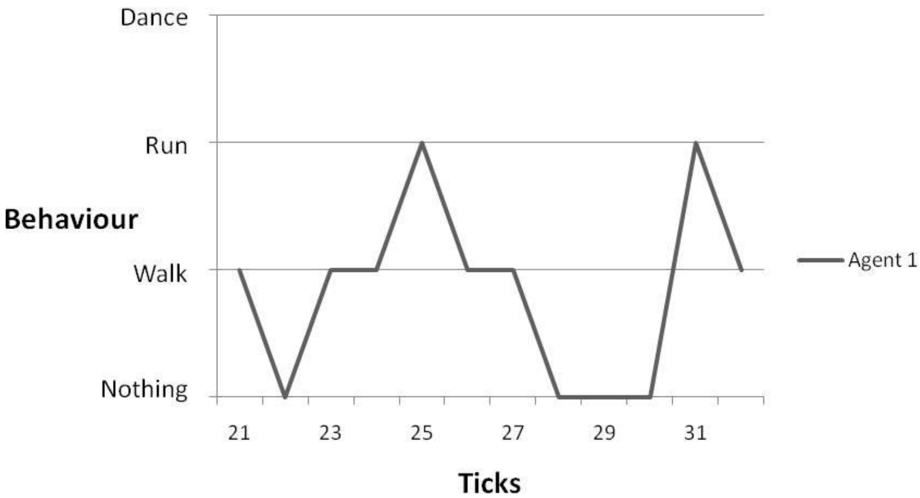

Figure 6.8: The behaviour that is exhibited by Agent 1 at each tick between tick 21-32.

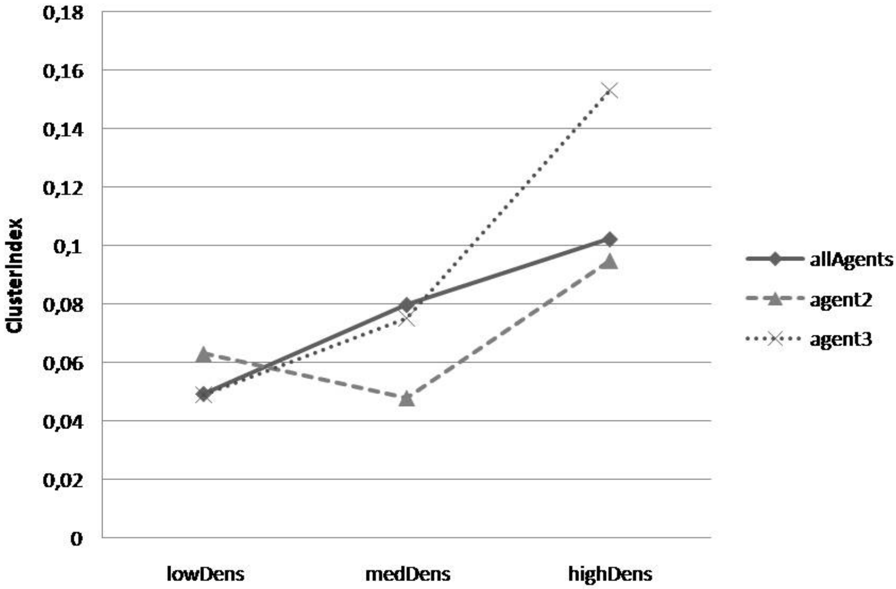

Figure 6.9: The cluster index (i.e. crowdedness) is related to the density level. In general, the cluster index rises as a consequence of a rise in density. When looking at individual agents, the cluster index may differ from the average.

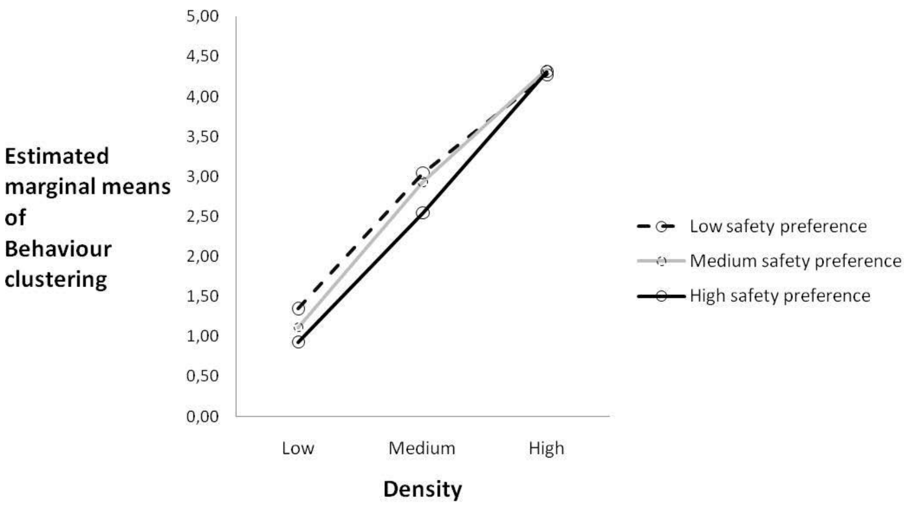

Figure 6.10: The estimated marginal means of behaviour clustering, visualised for all nine conditions.

Table 6.5: The descriptive statistics of the dependent variable: behaviour clustering.

Descriptive statistics					
Source	Sum of Sq	df	Mean Sq	F	Prob > F
Density Cond	454.67	2	227.34	17934.76	.00
Safety Cond	3.99	2	1.99	157.52	.00
Density x Safety	2.78	4	6.49	107.87	.00
Error	3.31	261	.01		
Total	464.76	269			

6.3.2 The group level

By establishing the effect of the manipulation at the group level the movement into the territory of the traditional social sciences methods is made where statistics is used to test the hypotheses stated in this thesis. All hypotheses will be addressed.

The relationship between density and behaviour clustering

Density was expected to show a positive relationship with behaviour clustering. A 3 (density: low, medium, high) x 3 (safety preference distribution: low, medium, high) ANOVA with behaviour clustering as the dependent variable (see Figure 6.10) reveals that there is a strong positive relationship between density and behaviour clustering ($F = 17934.76$, $df = 2$, $p < 0.001$), see table 6.5. The same can be concluded when visualising the nine conditions over time, see figure 6.11. The average behaviour clustering of the 30 runs for every time step shows a clear increase in behaviour clustering when comparing the rows (i.e. the levels of density) from the top row (i.e. low density) to the bottom-row (i.e. high density). In other words, when density rises, the number of dyads that is exhibiting the same behaviour at a given time increases. This implies that when density increases, more people will be behaving in the same way.

The relationship between safety preference and behaviour clustering

The second hypothesis expects a positive relationship between safety preference distribution and behaviour clustering. A 3 (density: low, medium, high) x 3 (safety preference distribution: low, medium, high) ANOVA with behaviour clustering as the dependent variable (see figure 6.10) reveals that there is indeed a positive relationship between safety preference distribution and behaviour clustering ($F = 157{,}52$; $df = 2$ $p < 0{,}001$), see table 6.5. Although there is a clear effect, it is not as strong as the effect of density on behaviour clustering when looking at the relative differences in the F-values. The contribution of the safety preference distribution to behaviour clustering is also clearly visible in figure 6.11. The difference in behaviour clustering due to safety preference distribution is smaller when moving from the left (i.e. low safety preference distribution) to the right (i.e. high safety preference distribution).

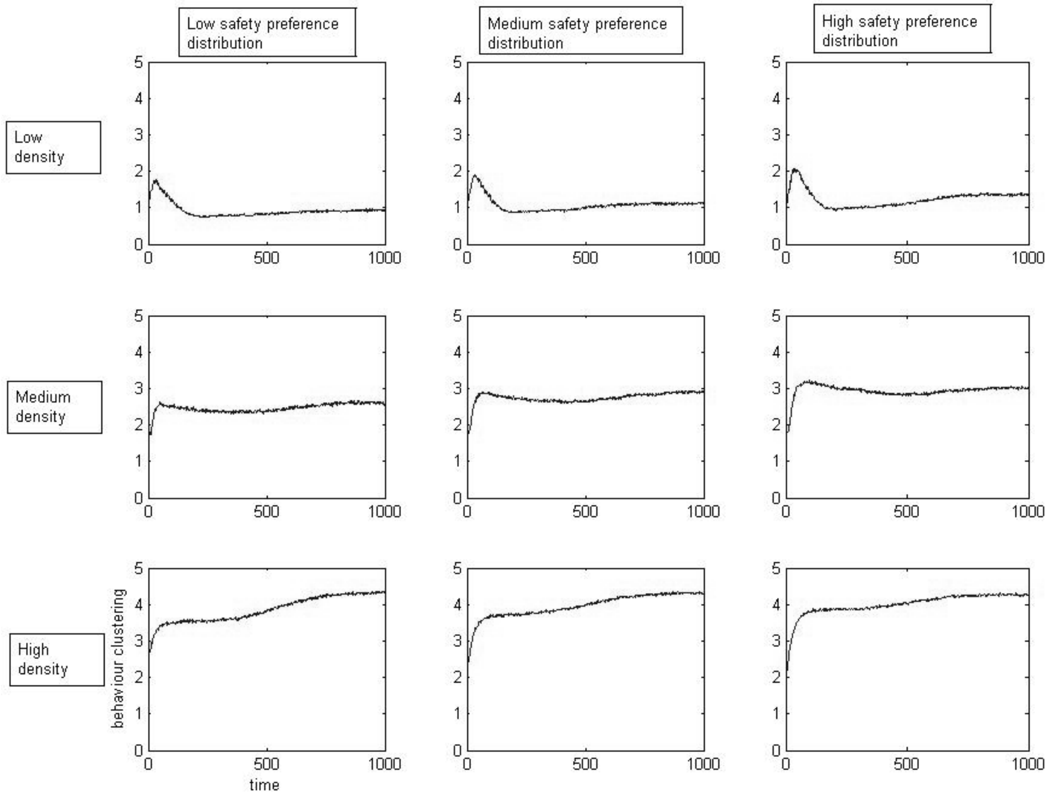

Figure 6.11: An overview of the behaviour clustering average for all conditions over 30 runs. The density levels (low, medium, high) are represented in the rows. The varying safety preference distribution(low, medium, high) is presented in the columns.

In other words, when safety preference in a crowd increases, the amount of dyads that exhibit the same behaviour at a given moment increases too.

The interaction effect of density and safety preference on behaviour clustering

In addition to the two main effects described above, an interaction effect was expected. The results of the experiment ($F = 107.87$, $df = 4$, $p < 0.001$) clearly show the presence of an interaction effect, see table 6.5. Like the safety preference manipulation, the interaction effect is not as strong as the effect of density alone. In figure 6.10 the mean comparison of this interaction effect is visible, with the effect being most visible in the medium and low density conditions. In other words, there is an interaction effect, but the effect is different than the effect that was expected. A density rise leads to an increased rise of behaviour clustering in a crowd with a medium safety preference. However, this stronger increase can mainly be observed when moving from the low to the high density condition. This implies that the interaction effect does not occur, as was expected, in the high safety preference crowd when comparing the rise width the low and en medium safety preference crowds. Moreover, moving from the medium to the high density crowd, the opposite seems to be the case: the rise of behaviour clusters 'stagnates' and results in a similar behaviour clustering for each safety preference condition, instead of the increase that was expected. These results show that the expected interaction effect only applies to the rise in density between low and medium density, and between the low and medium safety preference condition. In case of the high density condition, the interaction effect shows the opposite effect, i.e. the effect on behaviour clustering does not discern between the safety preference conditions.

6.4 Discussion and conclusion

In this chapter the role of density on behaviour clustering patterns in a crowd was investigated using a multi-agent simulation approach. The CROSS model contains of agents residing in a festival context. In the simulation, density (i.e. a physical factor) and the way density is interpreted (i.e. safety preference as a psychological factor) was manipulated. The outcome of the simulation experiment confirms the expectation that density plays an important role in the increase of the behavioural patterns shown in the CROSS model. Although the expectations of the main effects were confirmed, the interaction effect appeared to involve a relationship that needs more nuances than was expected. For an increase in density to the medium level, the stronger increase of behaviour clustering that was expected could be observed, but only for the medium safety preference group. To explain this phenomenon, further exploration is needed. With regard to the increase in density from medium to high density, the effect appeared to be the opposite from what was expected. The behaviour clustering increase is smaller when the crowd has a lower safety preference, while the expectation was a stronger increase in behaviour clustering. The suggested explanation is that a global rise in density does not have a strong effect on the local environment that is perceived by an agent. An agent has a restricted range of sight, which has the effect that, beyond a certain point, higher density levels do not result in additional behaviour clustering. A second reasoning implies that, due to a higher density, the environment of neighbouring agents does not change all that much, as movement (walking, running) is inhibited by high density. This could give rise to a stagnation of the number of patterns.

The main result of this experiment shows the important role that a physical influence factor, such as density, can play in crowd dynamics, directly as well as indirectly. Density directly influences freedom of movement and a preference for behaviour that is relevant to the safety goal, when dominant. However, indirectly, density affects arousal, which has an impact on the behaviour selection process in that it narrows down the search space with rigorous effects. This illustrates the importance of these pathways of influence. The indirect path, for instance, is context independent and supports a general understanding of crowd behaviour. In combination with the direct influence, i.e. including context, more specific interventions are possible, as the knowledge of the situation is more detailed due to the contextual knowledge. An example of the understanding that can be gained could be found in explaining aggression. The occurrence of aggression cannot be linked to density directly. However, if in a tense situation some individuals behave aggressively, high density may increase the probability of more people engaging in aggressive behaviour. To specify an explanation in this way, the detailed level that is needed to discuss crowd situations must be provided. It is important to realise that a non-semantical factor such as density, even though it does not cause a specific behaviour can intensify it. This helps to raise awareness of the role of context, as it is the context that will influence what *kind* of behaviour will be chosen.

Even though the results have limited implications on the real world, on a theoretical level two suggestions can be made with regard to crowd theory and crowd research: 1) an integrative theoretical approach that combines the relevant existing knowledge of the physical and social environment with the view of an individual as a cognitive system increases the explanatory power; and 2) a multi-level approach shows the importance of relating intra-individual, individual and group level dynamics to each other. It describes *which* crowd behaviour arises and *how* it is affected. By formalising and integrating only two theories the simulation was able to point out the importance of the role of density in crowd dynamics. The main contribution of the density experiment is that it gives direction to future crowd research. It is a welcome compass in a domain that is characterised by a huge amount of influence factors, intuitive pitfalls and a high level of complexity.

Future research on the relationship between density and crowds could further explore the role of density. In section 3.1.1 the three types of influence relationships were discussed that should be further defined in order to explain density. 1) the effect of density on physiology; 2) the effect of density on psychology; and 3) the effect of physiology and psychology on each other. The latter could be described as the social context affecting the arousal level, i.e. the psychology → physiology relationship. By distinguishing between situations between the way density is perceived (e.g. as nice or as not-so nice) and contributes to a group feeling, the explanation of density could be refined in terms of arousal change and thus the behaviour selection process.

Chapter 7

The role of leadership in crowds

The crowd at the beach festival described in chapter 1 represents a huge social event. Let's again take a bird's-eye view of the beach festival site, zooming in on the various identifiable groups. In addition to behaviour patterns of involving the queues at the bar and toilets, or the dancers in front of the stage, there were other very group specific patterns could be recognised. For instance, the group of visitors that attacked and chased the LEOs. The attack started when this group surrounded two LEOs, and formed a typical ring-shaped pattern. This was followed by the typical lanes when the attackers followed the withdrawing LEOs. Although these specific patterns are typical crowd behaviour patterns, they are a-typical in a festival context. The sequence of snapshots of this particular group keeps on displaying very group-specific behaviour, which is different from the other behaviour exhibited at the festival. While chasing the LEOs at a certain point, the group was stopped by a fence. Shortly after that, a few persons started shaking the fence, and a little while later, the majority of the group was tearing down the fence and continued the chase. Similar accounts can be given with regard to the count-down. The action was initiated by one or two persons, who were followed by a larger part of the group later on. The intergroup dynamics (i.e. the social context) were clearly dominant in the behaviour of these individuals.

This chapter will focus on exploring the role of leadership (i.e. a power relationship) in crowd behaviour patterns, using the CROSS model. From the density experiment it was learned that density can function as an intensifier on behaviour clustering. The density levels will therefore also be varied in order to explore the interplay with the role of leadership in crowd behaviour patterns, i.e. behaviour clustering. Current knowledge of crowd behaviour learns that social environment plays an important role (see chapter 2). The emergence of specific behaviour patterns is often the object of study. However, in order to gain a general understanding, it is necessary to concentrate on the mechanisms underlying behavioural patterns in general. Therefore, the emphasis lies on the rise of patterns of any kind of behaviour, instead of on the rise of a specific behavioural pattern.

Leadership is the phenomenon in which a person exerts more influence on his social environment than others influence theirs. Leadership research shows that exerting influence on others can be described on the basis of the attributes or skills of an individual, the specific context in which leadership is exercised, or the interaction that has taken place. Although in these studies most attention is paid to the leader figures themselves, implicitly as well as by definition all these studies involve interpersonal interaction. However, much less attention is paid to the other interaction partners: the followers, the persons being influenced by leaders. In order to understand crowd behaviour, this perspective is very important, as it is the 'followers' that do or do not exhibit certain behaviour. In this thesis, leadership is therefore considered an inter-individual process, in which a leader is defined from a follower's perspective. It is only the perception of someone as a leader that will affect the behaviour selection process of individuals, not the attributes or skills of an individual identified as a leader.

In this study, leadership will be explored in a simulated festival setting using the CROSS model (see chapter 3 and 5). In the CROSS model, leadership is considered as a social influence factor that affects agents according to the representation an agent has of others, whether they are leaders or not. This individual, local and subjective perception of leaders will influence agent behaviour via the changes in cognition, i.e. some behaviour becomes more relevant due to the social context. The agents in the experiment are heterogeneous in terms of what they perceive, as their perception is limited and depends on their position. They are also heterogeneous in terms of how they perceive other agents, e.g. leaders. In this simulation experiment, the agents that are regarded as leaders are fixed. They are the same for everyone and no leader is aware of being a leader himself. This is a simplification that allows to explore leadership, rather than a realistic representation of differences in the perception of others as leaders. For this reason leader agents are not modelled with specific attributes. Furthermore, the role of the perception of a leader is moved away from the leader to the internal representation of a follower. This is an important theoretical stance taken by following the CROSS model perspective. By varying the number of leaders, the influence that leaders exert will vary as more agents will perceive a leader.

7.1 The role of leadership

Crowds are social phenomena. Describing a large event, such as the beach festival, and especially the aggression of the group that was attcking the LEOs, triggers a lot of questions: "What causes people to initiate certain behaviour", even more interestingly "What causes people to join in such activities" and "What is the behavioural effect of perceiving someone as a leader in a crowd setting?". Answers to these questions would improve the insight into the role of an agent's social context. To explore the role of leadership, the CROSS model integrates several relevant theories and viewpoints on leadership at the cognitive level of description. As discussed in chapter 3, research on leadership concentrates mainly on the characteristics and skills of the leaders themselves, and on the context giving rise to an outcome of 'followers', for instance followers imitating a leader or being obedient. This thesis will deal with the perspective of the followers: what is it that affects a person's behaviour when he considers someone a leader? Leadership is explored by incorporating the subjective perception of someone as a leader in relation to behaviour expectation. The effect of perceiving someone as a leader concerns the fact that behaviour shown by the leader

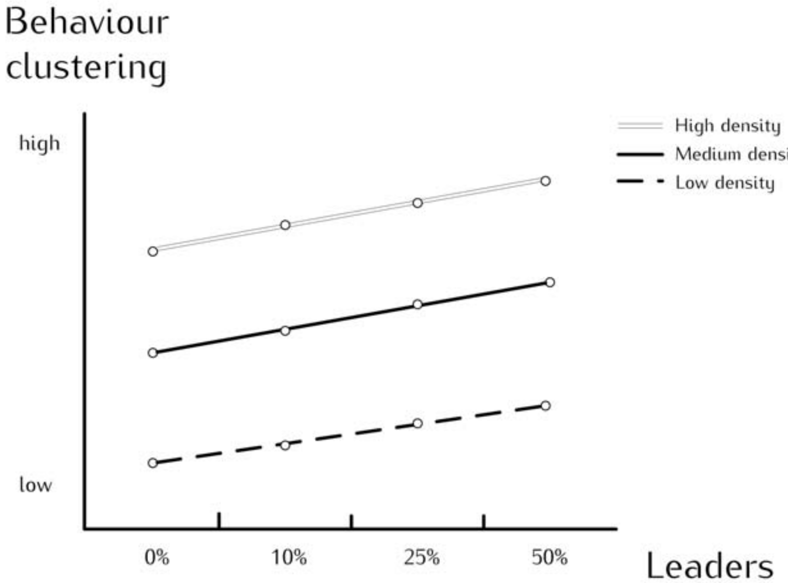

Figure 7.1: The expectation with regard to the role of leaders in crowd behaviour clustering.

becomes more relevant, which increases the probability of imitation.

The research conducted for this thesis specifically investigates how the presence of leaders influences behaviour clustering patterns in a crowd. For instance, does the presence of more leaders lead to a higher degree of behaviour clustering? What role does density play in this process? Like the previous chapter, a multi-level approach will be taken to answer the questions. Not only the relationship between leadership and behaviour clustering will be examined, but also the (intra-) individual level influences.

Leadership is expected to result in an increase in behaviour clustering. Leadership is defined as a process in which an individual exerts more influence on others than non-leaders do. The presence of a leader increases the probability of imitation. These expectations are visualised in figure 7.1. Behaviour clustering is expected to increase when the number of people that are perceiving a leader increases. A higher number of leaders will therefore increase behaviour clustering. At higher density levels, more people will be influencing each other, which will result in a rise in behaviour clustering (see chapter 6). An increase in density combined with an increase in the number of leaders is expected to establish an additive effect.

Table 7.1: Design of the leadership experiment: showing the twelve conditions of the leadership experiment resulting from the manipulation of the number of leaders and the density level.

Leadership	0%	10%	25%	50%
Density				
Low	Condition - 1	Condition - 2	Condition - 3	Condition - 4
Medium	Condition - 5	Condition - 6	Condition - 7	Condition - 8
High	Condition - 9	Condition - 10	Condition - 11	Condition - 12

The expectations can be formulated as the following hypothesis:

1. An increase in the number of leaders will lead to more behaviour clustering.

There are no specific expectations concerning an interaction effect. However, in order to be sure, it will be tested whether such an effect exists.

7.2 The CROSS experiment model

To investigate the role of leadership in behaviour clustering and to test the hypothesis above, a 4x3 experimental design was drawn up, manipulating both leadership and density. Leadership was manipulated in term of the percentages of the crowd that were leaders: `0%,10%, 25%,50%`. Density was manipulated as in the preceding experiment with `{low,medium,high}` density conditions. This manipulation and the resulting twelve conditions are displayed in table 7.1.

Before the leadership experiment, like the density experiment, can be run, the computational model must be prepared for experimental usage, i.e. phase 3 in the life cycle of simulation research (see section 4.2.3). Although this experiment focuses on leadership, the context and set-up of the experiment is the same as in the previous experiment. Consequently, most of the settings are the same. Each variable will be addressed, i.e. the leadership specific variables. The variables that are identical to those from the previous experiment will be set out in a summarised version of the previous chapter.

7.2.1 The leadership experiment variables

To perform a simulation experiment with the CROSS model, the independent variable (i.e. density) and the dependent variables (i.e. behaviour clustering and the life-history variables) need to be specified. Several variables (e.g. density, behaviour clustering) were already used in the density experiment and will be addressed only shortly in this chapter. For full details the reader is referred to the relevant sections in chapter 6.

The independent variables

In exploring the effect of leadership on crowd behaviour, two group level variables, *leader count* and *density* can be defined. These are the independent variables. `Leader count` concerns the relative amount of leaders in a crowd and will be represented as a percentage. The amount of leaders will be varied, distinguishing between *no leaders* and an increasing amount of leaders from *low* to *high*: `{0%,10%,25%,50%}`. Both `0%` and `50%` represent the extremes (i.e. no leaders and many leaders), whereas regarding the rising percentage of the leaders, more agents will observe and thus be influenced by a leader. `Density` concerns the group level description of a crowd, representing the number of people per m^2. It indicates crowdedness in three levels `{low, medium, high}`. This is identical to the manipulation in the density experiment, where a crowd of `{227, 681, 1275}` agents was created respectively. Please note that only density itself is manipulated, not the perception of density.

The dependent variables

Life-history variables. In explaining the group-level relation between leadership and density on behaviour clustering, individual *life-history* variables will be used. These life-history variables are measured for an individual or aggregate of individuals every time step, like in the previous chapter. For this experiment, the following individual life-history variables will be used: *observed leaders*, *behaviour expectation*, *behaviour utility*, and *behaviour*. During a simulation run, these in-depth descriptions of an agent will be used to give a rich explanation of the group level behavioural patterns. *Observed leaders* represent the leaders that are locally perceived by an agent. Of course, the perception of the number of agents and leaders is limited by the range of sight. In addition, the maximum number of visible agents is 13, given the range of sight. *Behaviour expectation* is an internal variable that represents the expectation whether a behaviour fact will satisfy an agent's social goal. This value is updated when an agent perceives a leader. It then changes the relevancy of a certain kind of behaviour according to the internal state at that moment. This is represented by *behaviour utility*. All these values play a role in the behaviour selection process, distinguishing between more suitable or less suitable behaviour at a certain moment in time.

The group level variable. At the group level, the same dependent variable is used as in the density experiment: *behaviour clustering*. Behaviour clustering describes a crowd behavioural pattern of identifiable subgroups composed of agents that exhibit the same behaviour at a given time step, i.e. crowd behaviour patterns. In other words, behaviour clustering captures the overall behaviour characteristics in one number, which is an aggregate of what the agents are doing (i.e. individual level → group level). Behaviour clustering is formalised as the number of dyads that exhibit the same behaviour at the same time-step, with the individuals in the dyads being in the physical vicinity of each other (see the (pseudo) algorithm 6.2 in the previous chapter).

Table 7.2 summarises the described variables that are used in this experiment to manipulate, to measure outcome and to explain crowd behaviour in the experimental

Table 7.2: An overview of the variables of the leadership experiment.

Leadership experiment variables				
Group level	Independent	Leadership [leader count - %]		{0%, 10%, 25%, 50%}
		Density [persons/m^2] [probability distribution]		Low = 1, Medium = 3, High = 5.5
	Dependent	Behaviour clustering		$[0, n(n-1)/2]$
Individual	Life-history	inter	Observed leaders	$[0, 13]$
			Behaviour	{walk,run,dance}
		intra	Behaviour expectation	$[0, 1]$
			Behaviour utility	$[0, 1]$

set-up.

7.2.2 Model settings

Now that the experimental design has been explained, the CROSS model can be specified for experimental usage. This includes specifying every aspect of the CROSS model: the physical environment, the social environment, the experimental settings and the agents themselves. The physical environment defines the relevant festival areas; the social environment describes the amount of agents and leaders as well as the social structure; and the agents are the actors in the simulation that are provided with relevant behaviour, knowledge and sensors for the festival context.

The physical environment

The physical environment is represented as areas that are walkable or non-walkable. Areas are represented by a collection of grid cells. The relevant areas for the festival scenario include: the toilets, the bar and the stage areas. Each area contains a point of interest that represents that area, for instance, the middle part of the front of the stage is attractive for the agents when moving towards the stage. A point of interest can thus be considered hard-coded common knowledge that concerns the meaning and implication of a certain place that can be regarded as a global perception. It does not concern regular perception, which is local. This simply means that being at or near a point of interest will satisfy a goal, for instance standing close to the stage will satisfy the identity goal (see sections 3.3.3 and 5.2.2).

The social environment

The social environment is that part of the crowd model that describes the group level characteristics. For this experiment, leadership (leader count), density and the social structure are defined on group level, where leadership is a specific formalisation to test the leadership hypothesis. Note that each group level description is translated into settings at the cognitive level, as this is the level where the actual influencing takes place.

Leader count indicates a percentage of the crowd size created as leaders. The creation of leaders conveys an internal representation of the agents that are leaders, which is represented as knowledge in the memory of all the agents. This piece of knowledge allows agents to identify 'the leaders' as leaders. The variation in leadership is realised in terms of the percentage of the crowd that is regarded as a leader. Four categories were chosen : 0%, 10%, 25% and 50%. By varying the amount of leaders in a crowd, these categories will affect the influence leadership has. An increase in the number of leaders will influence the amount of agents that is perceiving a leader, and thus the amount that is influenced by a leader.

`Density` indicates the number of agents that is created for a given festival terrain ($persons/m^2$). Three levels are defined: low density ($1\ person/m^2$); medium density ($3\ person/m^2$); and high density ($5.5\ person/m^2$). This density range is chosen to achieve different the behavioural effects without moving into extreme levels. These levels of density correspond with the number of agents that is created, respectively 227, 681, and 1275 agents.

`Social structure` is the last group characteristic. Social structure represents the structure of the group in terms of *who knows who*. For the festival setting, social structure is reflected by the percentages of the crowd that came to the festival in pairs, triplets or quartets. People usually attend a festival together with other people, usually in groups of 2, 3 or 4 individuals. Like every group level characteristic discussed, this setting also has consequences for the individual level. At this level, companion groups are formalised in terms of number of people that an agent regards as its friends. These relationships are reciprocal, i.e. if A is befriended with B, then B is befriended with A. In the simulation, as no empirical data are available, these groups are arbitrarily set to: 30% pairs, 30% triplets and 40% quartets.

Agents

Agents are the individuals in a crowd that 'live' in the simulated world while attending the festival. Agents generate behaviour and are affected by the situation they are in. Each agent has bodily and mental properties that need to be set. These are represented in a framework explained in detail in chapter 3 and 5.

The bodily factors that need an initial setting only concern the physiology variables of arousal, bladder and stomach. The initial settings of physiology are exactly the same as for the density experiment. *Arousal* represents the level of attention, which is initially set on an average value (0.5). This average value indicates that the agent is in an average state of attention, not asleep (0) or overly excited (1). The *bladder* and *stomach* are initially set according to a beta distribution that follows an approximation of a normal distribution.

The mental part of the agent is defined as a memory structure consisting of goals, facts and rules. *Goals* represent needs that an agent strives to satisfy up to a certain preference level. The four goals (identity, social, safety and subsistence goals) must be set with an initial satisfaction value as well as a preference value (see section

3.3.2). The preference for the *identity*, *social*, and *safety* goals is 'normally' distributed using a beta(5,5) distribution. Note that in the previous experiment, the safety goal preference was manipulated, whereas in this experiment this value is fixed throughout all conditions. The initial satisfaction value is zero for the identity and the social goal. Zero is chosen as the default initial value, as the initial settings are not important for the future satisfaction of both goals. In addition, starting with zero as the initial value will prevent the occurrence of strange onset behaviour at `t=0`[1]. For the safety goal, the initial satisfaction value is set to `0.5`, once again to rule out strange onset behaviour. The last goal is *subsistence*. The satisfaction of this goal is directly linked to physiology, i.e. to the status of the bladder or stomach. The preference is set homogeneously at `0.8` for all agents, which is quite high because, when dominant these basic needs can affect behaviour to great extent.

In addition to goals, memory consists of facts and rules, which each need their specific settings. The main difference between the density and the leadership experiment can be found in the content of the facts, i.e. the leader fact is added. *Facts* involve either behaviour facts or person facts. Both a *friend fact* and a *leader fact* concerns the internal representation of a friend or leader. This element enables an agent to recognise a fellow agent as a friend or a leader. This is indicated by a boolean value {`true,false`}. At this level, the crowd characteristics of the social structure are set. In other words, when an agent is assigned part of a pair, this means that two agents have an internal representation of each other as a friend. This reciprocity does not apply to leadership, as viewing someone else as a leader does not imply anything about how this 'leader' perceives the agent that perceives him as a leader. *Behaviour facts* are pieces of knowledge that represent the expectation of satisfying a goal when choosing this behaviour (see sections 3.3.2 and 5.2.2). This value is used to compare behaviour in terms of relevancy. The expectation values are fixed values that represent a relative value, not only between goals but also between behaviour. In table 6.3 in chapter 6 the expectations for each behaviour are given. The expectation values are selected on the basis of the festival scenario. The expectation values were assigned to each behaviour according to the degree of satisfaction of a particular goal. For example, dancing is expected to satisfy the social and identity goals, but not the safety goal. This is formalised by *dance* being expected to satisfy the identity goal with `0.3`, the social goal with `0.3`, the safety goal with `0.0`, and the subsistence goal with `0.0`. The behaviours *walk* and *run* are formalised in a similar way. Finally, the *rules* must be specified. The behaviour rules known by an agent are walking, running and dancing. Formalisation of these rules simply means that the agent is only able to exhibit behaviour it knows, and no others.

In general, the settings in memory represent the knowledge of an agent. In the simulation, this knowledge is fixed meaning that the expectations, the number of friends, who is a leader, and the behavioural options do not change over time. The settings determine the boundaries for the number of agents and the social structure they belong to. The settings also enable agents to read information from the world they reside in, to be affected by this world, and thus to be influenced in choosing their behaviour. An overview of the relevant settings of the CROSS model is visualised in table 7.3. Like in the density experiment, the simulation is repeated 30 times for each

[1]The onset behaviour can be called strange when the agent would act on the basis of a setting that is not affected by the context it is living in at that moment.

of the 12 conditions of the leadership experiment, with each run taking 1000 ticks. For the behaviour clustering measure, the average over a run is taken, excluding the onset[2]. The life-history variables are measured at each tick.

[2]The average is taken over tick [100,1000]. See the behaviour clustering pseudo-algorithm 6.2.

Table 7.3: The settings for the leadership experiment.

CROSS - Leadership experiment setting								
Physical Environment	Area	toilet, bar, stage		Non-walkable, point-of-interest (x,y)s				
Social Environment	Leader count	{0%,10%,25%,50%}						
	Density level	{low,medium,high} = {1.0,3.0,5.5}						
	Social structure	Pairs	30%					
		Triplets	30%					
		Quartets	40%					
Agents	Physiology	Arousal	0.5*					
		Bladder	beta(5,5)*					
		Stomach	beta(5,5)*					
	Memory	Goal	Identity	pref	beta(5,5)			
				satis	0.0*			
			Social	pref	beta(5,5)			
				satis	0.0*			
			Safety	pref	beta(5,5)			
				satis	0.5*			
			Subsistence	pref	0.8			
				satis	Physiology-based			
		Fact	PersonFact	Friend	{true,false}			
				Leader	{true,false}			
			behaviourFact	**expectation**	id	soc	safe	subs
				walk	0.3	0.3	0.2	0.1
				run	0.1	0.1	0.4	0.1
				dance	0.3	0.3	0.0	0.0
		Rule	walk,run,dance					

*Initialisation setting

7.3 Results

This thesis focuses on revealing the underlying mechanisms in crowd behavioural patterns. The CROSS model was designed to reflect the relevant levels of description. The precision and detail used to describe the CROSS model will now be applied to be able to describe, relate and analyse from a multi-level perspective. To relate leadership to behaviour clustering, a group level relationship is explored. However, in line with the CROSS model perspective, the route of explanation travels via the cognitive level. Therefore, the results of this experiment will be displayed starting from the path of influence at the cognitive and individual levels, before addressing the relationship at group level.

7.3.1 Looking under the hood - the cognitive and individual levels

Crowd behavioural patterns emerge at the individual level. Agents interact with their environment and choose behaviour on the basis of their internal state of that moment (see chapters 3 and 5 for a detailed description). Leadership was said to influence agents in by making the behaviour a leader exhibits more 'suitable' at a given time. When an agent perceives a leader behaving in a certain manner, the expectation of this behaviour fact to satisfy the social goal is increased.

The effect of leadership starts with the perception of leaders in the local vicinity. An increase in the amount of leaders at group level does not necessarily imply that all agents will observe a leader. The variation in the local perception of leaders (`Observed leaders`) for Agent 2 is displayed in figure 7.2 for agent 2. The amount of perceived leaders varies over time, as does the type of behaviour these leaders display. In accordance with the perception of leaders behaving in a certain manner, the corresponding behaviour expectation, in the agent's memory, is increased. Figure 7.3 shows the expectation values that fluctuate due to the changing amount of leaders that is observed. For example, Agent 2 is perceiving a running leader on tick 317, tick 322 and tick 327. The behaviour expectation of the BehaviourFact 'run' is peaking on the corresponding ticks.

In the behaviour selection process, the comparison between different kinds of behaviour is affected directly, as the expectation is employed to calculate the `utility`, which allows for comparing between types of behaviour and selecting the most suitable behaviour in a given setting[3]. Utility is based on the goal dominance settings and on the expectation value at a certain moment (see equation 5.6 in chapter 5). For each type of behaviour the utility values are showing similar dynamics as the expectation value due to the observed leaders (see figure 7.4). For example, none of the observed leaders are dancing. Consequently, the expectation for dancing remains constant. Apparently, the social goal did not change either. The utility value for dancing is therefore also constant.

In accordance with the internal state, a behaviour is chosen on the basis of these utility values. Figure 7.5 shows the behaviour of Agent 2. It shows that the Agent 2's dominant goals best.

The cognitive and individual level dynamics show that the group level manipulation of leadership moves via the way an agent and its internal state is affected. It was

[3] The comparison of behaviour is restricted by time

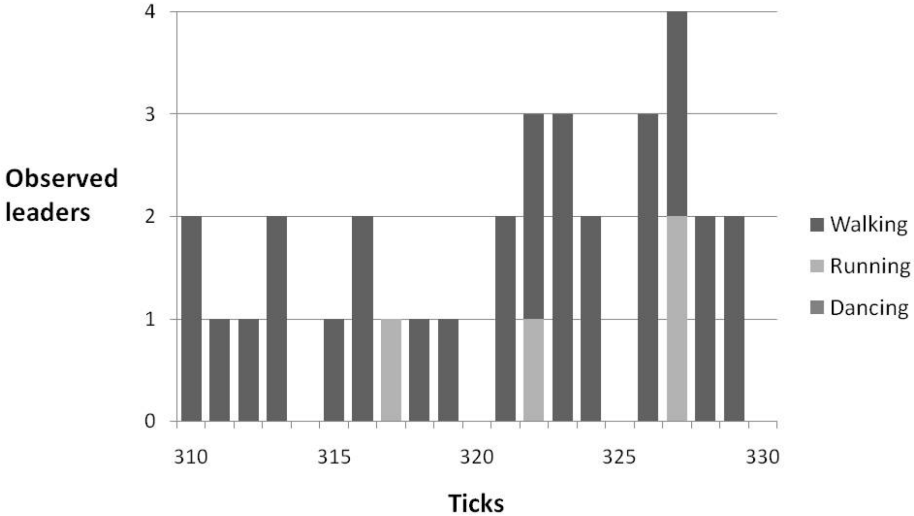

Figure 7.2: The number of leaders observed by Agent 2 together with the behaviour they exhibit between ticks 310-330. The leaders are displaying walking and running behaviour, but no dancing.

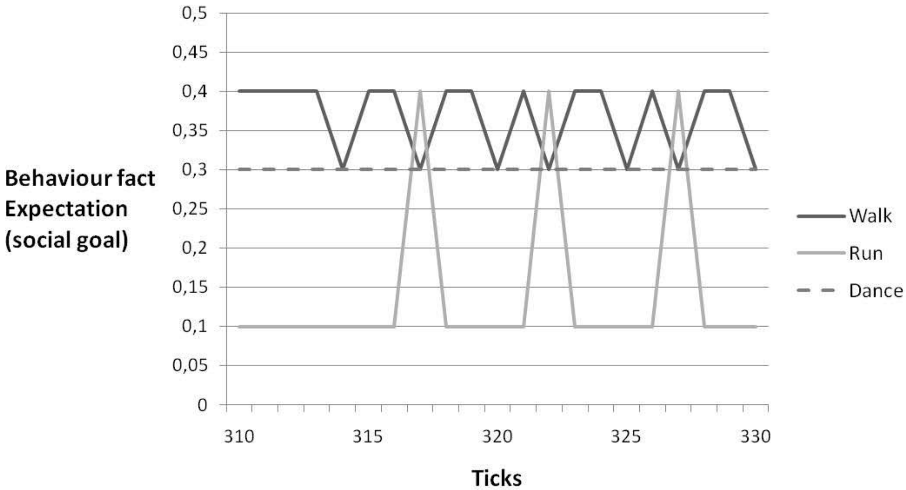

Figure 7.3: For each behaviour fact, the expectation of satisfying the social goal is shown for Agent 2 between ticks 310-330. When a leader is perceived, the expectation of the behaviour exhibited by the leader is influenced.

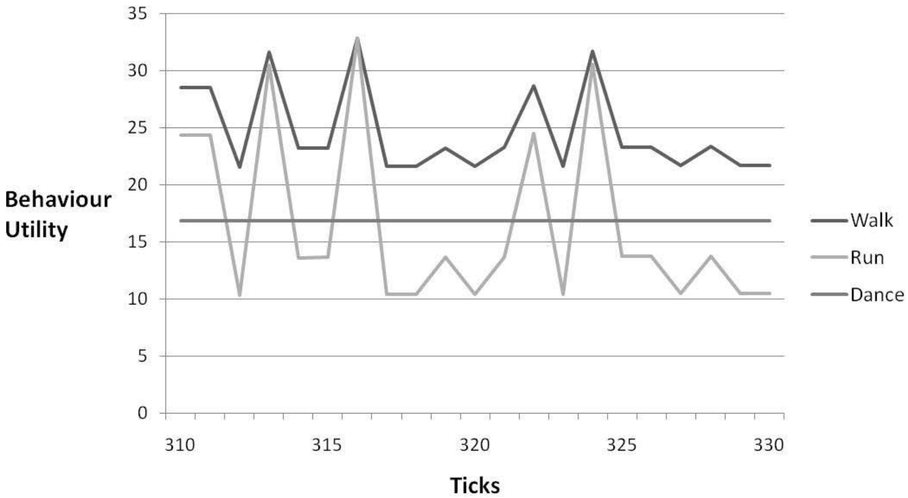

Figure 7.4: The utility for each behaviour (walk, run, and dance) of Agent 2 between ticks. The utility value represent the relevancy of certain behaviour given the setting at that point. It is used to compare and choose behaviour.

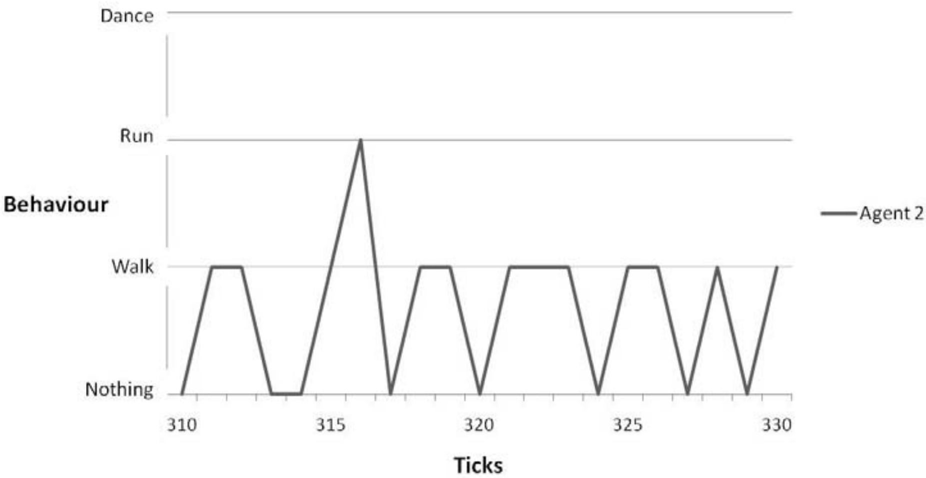

Figure 7.5: The behaviour that is exhibited by Agent 2 on each tick between ticks 21-32.

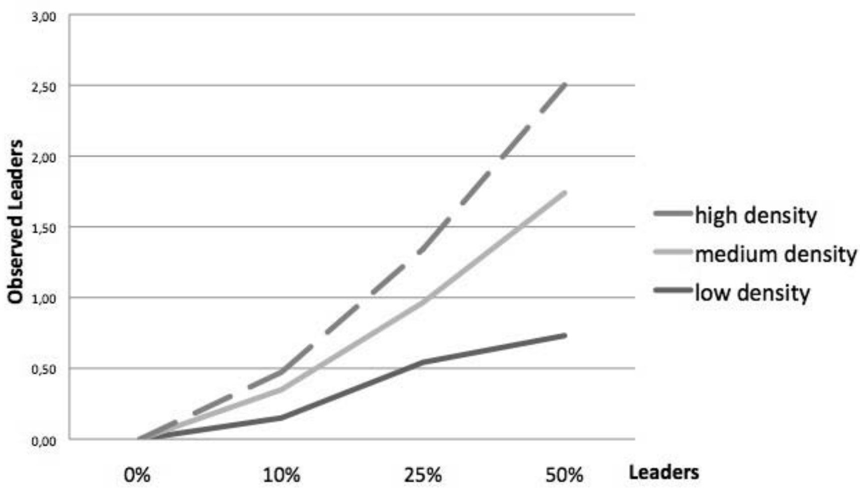

Figure 7.6: The average number of leaders that are observed by agents for each of the different leadership {0%, 10%, 25%, 50%} and density {low, medium, high} settings.

indicated in the experiment that when moving between the levels, manipulation at the group level would affect the agents differently, as each agent has its own unique environment. However, when moving back to the group level, the behaviours are reflected in a general effect. Figure 7.6 displays this general effect by indicating, for each condition, the overall number of leaders that are observed by agents.

7.3.2 The group level

The effect of the manipulation at the group level is tested against the stated hypothesis, using statistics as a method from the traditional social sciences, like in the density experiment.

The relationship between leadership and behaviour clustering.

Leadership was expected to demonstrate a positive relationship with behaviour clustering. The 4 (leader count: 0%, 10%, 25%, 50%) x 3 (density: low, medium, high) ANOVA with behaviour clustering as the dependent variable, see table 7.4, shows that there is a significant relationship between leadership and behaviour clustering: ($F = 309.90$, $df = 3$, $p < 0.001$). However, this effect seems to be marginal, especially compared to the significant effect of density on behaviour clustering ($F = 170387.67$, $df = 2$, $p < 0.001$). The same conclusion can be drawn from the visualisation of

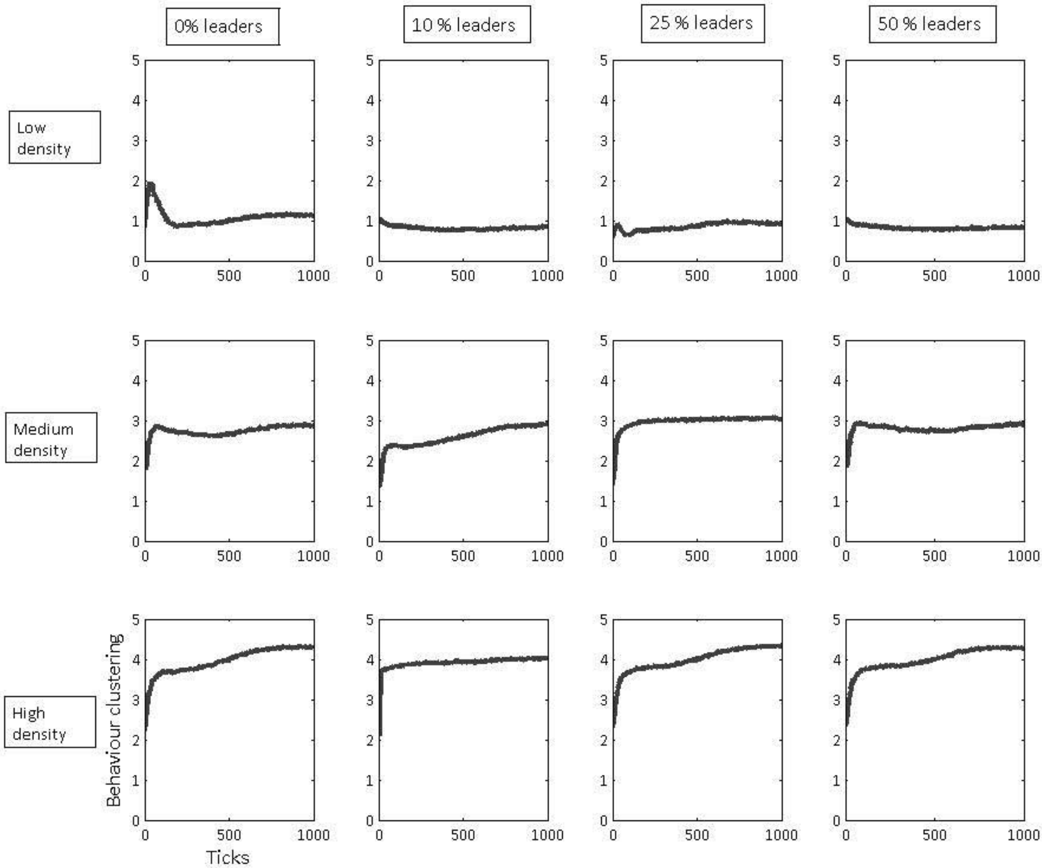

Figure 7.7: Overview of the behaviour clustering average for all conditions over 30 runs. The rows represent the density levels {low, medium, high}, whereas the columns represent the leader count percentage {l0%, 10%, 25%, 50%} is varied given the columns.

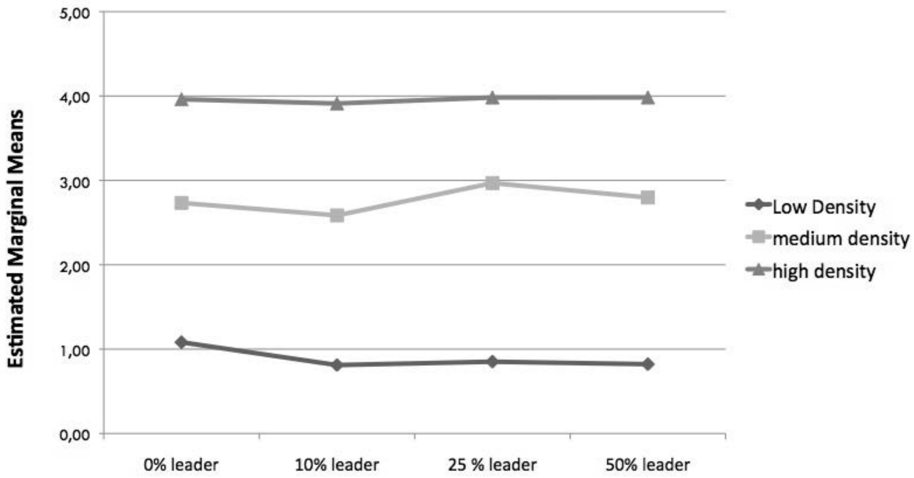

Figure 7.8: The estimated marginal means of behaviour clustering, visualised for all 12 conditions.

Table 7.4: The descriptive statistics of the dependent variable: behaviour clustering.

Descriptive statistics					
Source	**Sum of Sq**	**df**	**Mean Sq**	**F**	**Prob > F**
Leader Cond	1.57	3	.52	309.90	.00
Density Cond	574.17	2	287.09	170387.67	.00
Density x Leader	2.27	6	.38	224.58	.00
Error	.59	348	.00		
Total	2901.93	360			

the 12 conditions over time in figure 7.7 . The average behaviour clustering remains fairly stable, comparing the columns (i.e. leader count) from left to right. In other words, when there are more leaders agents, the increase in agents that exhibit the same behaviour as other agents in their vicinity is minimal.

7.4 Discussion and conclusion

In this chapter, the role of leadership on behaviour clustering patterns in a crowd was investigated. Unlike the previous experiment, the agents in a festival context were not only exposed to different density levels (i.e. , a physical factor), but also to leadership (i.e. a social factor). The outcome of the simulation experiment leads to a rejection of the expectation that leadership plays an important role in the rise of behaviour patterns. What does this mean? Leadership does affect the type of behaviour an individual is likely to imitate. The individual life-history variable shows that this imitation effect takes place. However, imitation does not lead to an increase in behaviour clusters. Behaviour clustering represents the amount of dyads that exhibit the same behaviour at the same time. This number increases rapidly when behaviour becomes more homogeneous. This is not necessarily a consequence of perceiving leaders, as different leaders can influence in different directions. The explanation of the result of the experiment probably lies in the fact that behaviour clustering does not distinguish between behaviours. Leaders will influence a certain type of behaviour, and the overall effect could even be a decrease in the amount of behaviour clustering. Imagine five agents in each others vicinity that are dancing. The perception of each other dancing will stimulate repetition of the current behaviour. However, when a leader walks by, he can 'overrule' this behaviour pattern by enhancing the probability of walking for the agents that are perceiving this leader. The results actually emphasise the importance of the choice of outcome variable. Apparently, behaviour clustering as defined here is too abstract to catch the effects of leadership. To explore leadership, and probably other social factors as well, the outcome measure should be able to distinguish between the types of behaviours. The exploration of general mechanisms can still continued, but the level of abstraction should not exceed the level on which the behaviour types exist. The role of the social environment is thus related to the type of behaviour clusters that arise. More specifically, leadership can be said to influence the types of behaviour exhibited and thus to affect the direction in the atmosphere of a crowd setting, e.g. hostile or peaceful, passive or active.

The social context influences *how* behaviour will be affected, and thus *which* specific behaviour will be chosen. This awareness is the main insight gained from this experiment. In the search for generic mechanisms, it is therefore crucial to define a dependent variable that is sensitive to specific behaviour types. In line with the current dependent variable, behaviour clustering could, for instance, be specified in terms of the amount of dyads, based on both agents in the dyad, displaying specific behaviour, such as dancing. This refinement would enable to explore leadership by relating the type of behaviour that leaders exhibit to the increase in behaviour clustering of that specific behaviour. Consequently, the design of the experiment should to be changed as well. An example of an experiment testing the effect of leadership would be to compare the behaviour clustering of dancing. Let's say that 10% of the crowd is set to dancing during the simulation. In one condition this 10% is made up of leaders, whereas in another 10% of the agents is dancing in a crowd without leaders. Comparing the number of dancing clusters in the two conditions would make the group level consequences of leadership clear. To conduct this kind of experiments, the CROSS model must be adapted slightly and the experimental design must to be thought through[4]. This refinement makes it possible to explore the social context more deeply.

The importance of the social context has real-world implications. The leadership

[4] The design and adaptation of CROSS to perform this experiment involves specifying not only behaviour clustering for a specific type of behaviour (i.e. the dependent variable), but also the settings of specific agents and the way they behave. It is not simply a matter of defining 10% with a fixed type of behaviour, also their spatial position needs to be fixed in order to compare the influence both conditions have. Moreover, it has consequences to freeze behaviour, not only in the way behaviour is chosen by a specific agent, but also in the way others are affected. Changing the behaviour of the social agent entails changing both the physical and social context, and thus whether agents are influencing and how they are influenced. These dynamics must be taken into account in the experimental set-up.

experiment explores the power-relationships in the CROSS model. In this experiment, leadership is represented in a basic form that does not allow for making claims about leadership itself. The contribution of this experiment lies in a different aspect. The experiment illustrates a different way of looking at a phenomenon such crowd behaviour. Instead of sticking to a traditional common-sense view, e.g. the hierarchical view on leadership, a dynamic, context-sensitive stance has become necessary. By framing theories and ideas within the structure of the CROSS model, the way of explaining and thinking about group dynamics is already changing. Leadership research can benefit not only from this interaction perspective, but also from the concreteness in defining leadership that this approach calls for.

For crowd research, the main contribution of the experiments lies in the fact that it can give direction to further research. As discussed in chapter 3, leadership concerns the subjective perception of someone else as a leader, but it may also concern the perception of oneself as a leader. Therefore, it would be interesting to explore these leader-follower dynamics and see how they affect the leader's choice of behaviour when he considers himself as a leader and perceives others imitating him. It addition, it would be interesting to investigate what would happen if someone did not perceive himself as a leader but was imitated anyway. If the fixed setting of the few people regarded as a leaders were changed into a heterogeneous subjective perception, the simulation would become more complex, but also more realistic. In social simulation studies concerning leadership, leadership arises. It would be interesting to include this aspect too. It would involve defining all relationships with other agents as power-relationships that are subjectively perceived. Some relationships are equal (i.e. between friends), some do not have any value (i.e. with strangers), some are unequal (i.e. exerting more/less influence). These relationships may change over time and leadership may emerge as a pattern due to the subjective perceptions of a set of agents or to the behaviour these agents display.

Experiments with the CROSS model clearly demonstrates its conceptual power due to the way it forces detail and preciseness, which in return can be used to explain and analyse. Even when using a basic representation of leadership and density, both experiments explored a physical as well as a social factor. To represent an individual in terms of a cognitive system allows for incorporating theories from the social and behavioural sciences, which does not only build a bridge, but also leads to cross-fertilisation. Even though the conceptual power in this project is clear, further implementation, validation and experimentation will add more precision to the above mentioned contributions.

Chapter 8

Discussion and Conclusion

This thesis sought to answer the question:

> Which mechanisms underlie crowd behaviour patterns?

In order to find an explanation for the generic mechanisms that underlie behaviour patterns, the first step was to study literature. Several things can be concluded from the literature. Generally, a lot of the literature on crowd phenomena is written from a practical perspective. From this literature, it becomes clear that practitioners are mainly experience-driven and only rarely act informed by the latest crowd research (Adang, 2006). However, nor does science provide the systematic knowledge that practitioners need at this stage, in spite of the existence of a body of crowd research. Modern crowd research provides empirically based descriptions of crowd behaviour, mainly focusing on specific phenomena, especially on disorder and emergency situations. Altogether, these studies do identify a number of influence factors that are supposedly relevant for crowd behaviour. However, explanations for *why* and *how* these factors exert the supposed effect are rare. The result is a large body of theories that are untestable in their present form. The studies that do provide an explanation (e.g. (Adang, 1998, 2010; Reicher & Levine, 1994; Reicher, 2001)) tend to give a specific type of explanation that only applies in a specific type of situation, , usually involves disorder or emergency situations. Disorder studies focus on explanations in the social context, whereas emergency studies focus on explanations in the physical context. Having said that, modern crowd research provides three important insights:

- Crowd behaviour is generated by individuals, i.e. agency is at the individual level and not at the group level.
- Crowd behaviour is context-dependent. Context includes both the physical and social environment.
- Crowd behaviour is dynamic: there is a continuous interaction between individuals and the environment over time.

These insights reflect the importance of the interplay between individuals and their environment in generating crowd behaviour patterns. With regard to these insights, one cannot help but notice that the explanations given do not incorporate the way individuals process information and choose behaviour. Consequently, in crowd research, references to theories from the cognitive sciences are rare.

Given the current state of knowledge gained from literature and the fact that the field is restricted in the sense that it cannot perform controlled experiments, two requirements can be formulated. These requirements have to be met in order to increase the understanding of the mechanisms that underlie crowd behaviour patterns: 1) a theoretical model that reflects the dynamic interplay between individuals and the environment is required, and 2) a method that allows to test this theory is required. The CROSS model incorporates these two minimal requirements. The CROSS model represents a theory of crowd behaviour that was explored by means of simulation experiments.

The CROSS model is developed by using an integrative, multi-level and situated approach. The model is integrative, as relevant knowledge from the social and cognitive sciences is integrated into the framework. The model has multiple levels, including the level at which behavioural patterns emerge (i.e. the group level), the level at which behaviour is generated (i.e. the individual level), and the level at which behaviour is affected (i.e. the cognitive level). The model is situated because individuals are embodied (i.e. the physical aspects of having a body) and embedded (i.e. the mental state related to a context and experience at a certain moment). The CROSS model thus incorporates the three main insights from modern crowd research, plus it moves a step further in describing behaviour at the cognitive (i.e. intra-individual) level. The cognitive level is a reflection of the understanding of individuals as human information processing systems. Two main processes describe the interplay of an individual with its environment, involving perception and behaviour selection. The level of detail provided by the cognitive level of description allows for relating the level at which behaviour is affected and generated (the cognitive and individual levels) to the level at which patterns emerge (the group level). To answer the research question, this multi-level approach is taken.

This integrative, multi-level and situated approach offered by the CROSS model leads to detailed explanations. It also forces explicitness when incorporating theories and ideas and helps to make them more concrete and precise. The framework demands specific descriptions of crowd behaviour, including the way individual behaviour is affected and generated, what it means to have a body and to be embedded, what it means to be placed in a physical and social context, and finally how this all evolves over time. The development of a computational model contributes to the explicitness in the CROSS model to an even larger extent. It shapes the way in which every potential variable, idea or theory is framed, because these variables must be so specific that they can be represented in a form that can be understood by a computer. These fundamentals, together with the precision that a computational model enforces, entail a certain view on crowd phenomena. When a potential factor, idea or theory is considered, it is framed, which clarifies immediately whether the idea or theory is precise enough for this model. For example, leadership research mostly concentrates on describing how an effective leader can be found, how a leader can be 'made' or in what kind of setting a leader becomes effective. The leadership literature does not focus on describing how a leader actually influence other people, moving beyond terms like charisma or motivation. From the perspective presented in the CROSS model, the actual influencing is the first point of focus, a point that is crucial in describing the behavioural dynamics. The CROSS perspective forces to concretise this specific part of influencing concerning leadership. The differences in perspective become immediately clear, which allows to distinguish between the relevant and irrelevant parts of those ideas or theories. Furthermore, the CROSS perspective supports the incorporation of the relevant factors, ideas and theories without losing the overview in the multitude of potential factors, ideas and theories. In other words, CROSS supports both a multi-disciplinary and an integrative approach. With regard to the CROSS model itself, the level of concreteness results in transparency concerning about the strong and weak points of the model. This stimulates the iterative process of improving the model where needed in order to answer the research question.

Simulation was chosen as the method to test the model. Simulation provides both experimental freedom and a rigid scientific structure, which is exactly what crowd research needs. The design approach that was chosen to represent the CROSS model in a computational form is multi-agent systems. Multi-agent systems allows to incorporate all the elements that are required: the multiple levels, the individual-level richness (i.e. the cognitive level), the role of context and dynamics. To be able to conduct experiments, the theoretical model was formalised into a computational model. For this step, each concept and/or relationship had to be defined in variables and methods that could be understood by a computer. Formalisation is an important and challenging step that involves the use of existing knowledge or data and a creative approach[1] in order to transfer the ideas into code. In the transfer analogy, intuition and the expertise of others play a role, but these all have their pitfalls. To be able to explore new areas, testing (i.e. verification and validation) is crucial (Abbott, 2003). Testing reveals the strengths and weaknesses of the model and therefore the credibility of the outcome.

Two experiments were conducted with the CROSS model to gain a better understanding of crowd behaviour patterns. One experiment explored the effect of a physical factor (i.e. density) on behaviour clustering, and the other explored the effect of a social factor (i.e. leadership) on behaviour clustering. When interpreting the results, it is important to realise that the exploration of density and leadership refers to the CROSS model and not to the real world. This makes any real world inference a hypothesis rather than a fact. Each experiment led to several factor-specific insights, but, most importantly, to insights at a more generic level. In the density experiment, it became clear that density is an important factor to take into account when investigating crowd behaviour patterns, because it has a strong impact on what an agent perceives as well as on which behavioural options an agent has. Furthermore, density also has an indirect effect that does not concern only the physical environment. Fluctuations in density level can change the social environment, which influences *what* is perceived. This is because perceiving more people implies being influenced by more people. The leadership experiment demonstrates the importance of the role of the social context in behaviour specific choices. Which behaviour is relevant or suitable appears to be a function of both the social environment and the internal state of an agent. The experiments show that the physical context describes a more generic relationship by influencing the behaviour selection process in terms of the time that is

[1]Creativity refers to the innovative part of scientific research. The scientific imagination a psychologist uses to design a good experiment for instance. See Abbott (2003) for heuristics in being 'creative'.

available to compare and choose behaviour. The social context, however, describes a more specific relationship as it is the affected behaviour-specific aspects that change the type of patterns that arise, not the pattern size itself.

Even though density and leadership were represented in a basic form, the experiments conducted with the CROSS model already illustrate the distinctive contribution of the CROSS model compared to other, traditional models, mainly by the level of detail provided and the multi-level description. In addition, the results of the experiments confirm the importance of the role of context. For instance, it is clear that density has a stronger effect than solely the bodily impact. It is important to realise that a physical influence factor, such as density, does not necessarily lead to a specific *type* of behaviour. It can, however, affect the behaviour patterns that arise indirectly. The leadership experiment, on the other hand, stresses the role of social context in the type of behaviour that emerges. Both the density and leadership experiments raise several important issues in relation to seeking an answer to the research question.

In general, the research of this thesis demonstrates the importance of the interplay between the physical and social context in behaviour. Due to the monodisciplinary orientation of most crowd research, the interplay between multiple factors is traditionally neglected. Obviously, including context should be based on relevance, rather than on field-specific preferences. Due to the multitude of potential factors, simplicity is needed in order to understand the dynamics of the model. It was not the aim of this thesis to create a "complete" model that would incorporates all potentially relevant influence factors at this stage. In fact, this would make the model less transparent, making it more difficult to find the mechanisms. The model is developed in such a way that theories and ideas can easily be integrated and that factors can easily be changed, replaced or added. For this study, a basic formalisation was provided that included one physical and one social factor. The flexible and easily adaptable character of the structure is suitable for exploring general mechanisms, allowing for all kinds of factors to be included easily. From the perspective of crowd research, this thesis represents an unusual approach, applying a design methodology within an empirical methodology. The design and formalisation of a simulation is part of an empirical cycle, like other empirical research. This thesis demonstrates that this approach can lead to meaningful results.

8.1 Answering the research question

The research question can be answered by combining insights from the literature, the theoretical/computational CROSS model and the results of the experiments. In the first place, *the mechanisms that underlie crowd behaviour are the same mechanisms that give rise to behaviour in general.* This is an important realisation as it makes clear that crowd behaviour should not be considered as a special kind of behaviour that needs its own set of dedicated theories. Therefore, the whole body of knowledge on human behaviour is potentially relevant. This answer is actually defining the search space in looking for mechanisms. Secondly, *explaining the mechanisms underlying crowd behaviour patterns always requires a complete image of the interplay between individuals and their context*. This does not imply completeness in the sense that all relevant factors must be incorporated; it means that the interplay between the factors one chooses to describe in relation to both context and individuals must always be addressed. It is impossible to meaningfully study individuals isolated from their context; placing them outside a crowd context would make no sense. However, exclusively regarding the context without considering the individual perspective would be meaningless too:'What affects this individual?' and 'How does the individual interpret this context given his current internal state?'. To reveal the mechanisms, the interplay between individuals and their environment must always be taken into account, regardless of the factors under consideration. Thirdly, several generic mechanisms can be derived:

- The physical context predominantly determines what influences behaviour, thus affecting the size or number of crowd behaviour patterns.
- The social context predominantly determines how behaviour is influenced, thus affecting what type of behaviour is exhibited in crowd behaviour patterns.
- The internal state of the cognitive system determines which behaviour is chosen.

The physical context predominantly determines what influences an individual in terms of what he is able to perceive and what could thus potentially affect his behaviour. For instance, the function of a fence may be to block the perception of an attractive point, to minimise pushing or to guide movement in a certain direction. Of course, there is no direct effect on behaviour, but there are direct constraints on the freedom of movement. The physical context does not distinguish behaviour on the basis of contextual relevance, but on the basis of practical possibility[2]. The social environment predominantly affects an individual concerning the type of behaviour that he considers more relevant in a certain setting. The different influences concern the internal representations of a person's relationships with others (i.e. interpretation). In the end, the individual will choose behaviour on the basis of his internal state that is continuously changing due to the influence of the context.

8.2 The contribution of the CROSS model

To develop the CROSS model, theories and ideas were used and adapted from a diversity of research areas. In turn, the CROSS model can contribute to these research areas too, exactly because of its integrative approach. The CROSS model has researchers and practitioners look at crowds from a different and narrative perspective. By doing so, it sheds a different light on the traditional way of using theory and methods in relation to crowds. Below, the contribution of the CROSS model to crowd research, to the cognitive sciences, to the social sciences in general, and to computer science/simulations will be set out. In addition, the practical implications of the CROSS model will be discussed.

8.2.1 Crowd research

The main contribution of the CROSS model obviously concerns the field of crowd research. This aim of this thesis was to develop a generic, testable theory as well as a

[2] Please recall that the extreme settings are not taken into account here. In case of an emergency (e.g. facing a fire), the context does directly influence the type of behaviour (e.g. fleeing). The aim is to describe a general principle that is derived from the influence the physical context has.

methodology for understanding crowd behaviour. The answer to the research question reflects the main theoretical contribution: the only way to understand crowd behaviour is by explaining behaviour in general. The CROSS model expands the body of existing knowledge on crowd behaviour patterns by incorporating theories on individuals, especially theories in which individuals are consideered human information processing systems (i.e. cognitive systems). Both the relevance of context and the way influences act on an individual concern crucial steps towards a better understanding of this complex phenomenon. The methodological contribution lies in the use of simulation as a method. Simulation fulfilled the need of crowd research to conduct experiments and thereby test theories. Simulation provides in the methodological steps to gain a better understanding of crowd behaviour. Experimental freedom is limited only to the level of description and detail that is chosen. A high level of detail was used for the cognitive level, providing a lot of richness in the explanations. The formalisation of the theoretical CROSS model adds even more detail and concreteness, and, in this way, leads to an adapted and thus new version of the theory it represents.

8.2.2 Cognitive sciences

The CROSS model is built on the view of an individual as a cognitive system, i.e. a human information processing system. This view originates from the cognitive sciences. The functional-level description of the mental processes was adopted from cognitive architectures which originates from a perspective to develop a unified theory of cognition (Newell, 1990). In developing the CROSS model, embeddedness is reflected by the social setting of a crowd event. Cognitive representations of social concepts are hard to find in cognitive sciences. This is mostly due to the fact that social aspects are not the point of focus for cognitive scientists, who tend to study individual cognition in depth (Sun, 2008). When studying human cognition, they focus on so-called higher cognition, including planning, language, and reasoning, and refrain from making direct references to the social environment of individuals. In this thesis, the focus lies on behaviour in a dynamic social context. In other words, the social environment is crucial. Although the types of behaviour involved generally concern lower cognition, it is fairly complex to represent them due to the constantly changing nature of the world and the complexity of social interactions.

The research in this thesis concentrates on understanding behaviour in a social world. By taking the stance of an individual as a cognitive system, the exploration concerns the social world being represented at a functional level. For the cognitive sciences, this is bridging their field to the social sciences. In addition, it evokes a discussion on how to represent the social world on the cognitive level. After all as Boden puts it: "Cognitive science is not the science of cognition. Or rather, itis not the science of cognition alone." (Boden, 2008, p. 669).

8.2.3 Social sciences

For the social sciences, the same argument as for the cognitive sciences holds: the integrative, multi-disciplinary and computational approach explores the boundaries of the field and sheds new light on traditional views and approaches. The social sciences are mainly concerned with theories that relate a minimal set of relationships, use a monodisciplinary view, and employ an intentional level of description. New insights can be gained by taking a different perspective on crowd behaviour. The CROSS model, for instance, broadens the scope to describe a wider range of behaviour and contribute to a better understanding of crowd behaviour in general. Isolating instances of behaviour or interactions from the event would provide insight into very specific situations, but not into the general dynamics in a crowd. The use of a structure in which existing theories, integrated with other theories, can be placed allows for the coverage of a broader range of behaviour. The flexible and easily adaptable character of the model allows for the comparison of multiple theories, either together, isolated, or in comparison to each other. In addition to taking a broader perspective, the use of knowledge from other domains concerning human behaviour (e.g. the cognitive sciences) is complementary for the social sciences. Up until now, these other domains are not used very often. It seems that the social and cognitive sciences do not interact with each other, even though they do share research topics. Of course, their focus is different but the topics are still the same. The integration of these theories into the CROSS model can facilitate using knowledge that is relevant and available. The level of description used in the CROSS model can also be seen as a contribution to the social sciences. The cognitive level adds detail, concreteness and precision to a theory, but even more importantly, it makes the theories comparable as they are all described in a similar way. In this way, communication about theories and ideas is made easier and the possibilities for integration become more realistic. In addition, the use of simulation in the social sciences enables to study complex research areas, such as social processes, and to explore the effects of different settings.

8.2.4 Computer science/simulations

In general, computer simulations of human behaviour in general are mainly developed in terms of computer science notions, such as reusability of software patterns, object-oriented programming, scalability, computational cost, or 2D/3D visualisation, to name only a few. For example, simulations of crowds tend to simulate behaviour, which usually involves locomotion or movement on the basis of physical characteristics and laws. This way of modelling behaviour, without taking the social context into account, will always limit the behaviour an agent will be able to display. This study shows that modelling behaviour is not easy, but most importantly, it shows that the role of context, both physical and social, should not be ignored.

This research and other social simulations describe behaviour, not the physical laws of movement. A simulation based on physical aspects alone would not be able to reproduce the group that turned against the police at the beach festival in Hoek van Holland, while others continued partying. This shows not only the importance, but especially the potential and applicability of developing a simulation that incorporates human behaviour[3].

[3] To develop simulations that are capable of representing realistic or believable behaviour does not necessarily imply using computationally heavy models. This depends on the simulation and the knowledge available of a certain situation. The aim of this thesis was to gain knowledge that required a high level of detail. Whenever the knowledge is available to the modeller, a formalisation to more simple rules allows for the development of lighter behaviour models.

8.2.5 Practice

Although the research in this thesis represents a theoretical study on crowd behaviour, including an exploration in a simulated world, the potential contributions for practice are already visible. The CROSS model raises awareness for the important ingredients determining crowd behaviour: context, individuals and the dynamics between them. Too often, the tendency is to look at undesired outcomes, without taking the relevant elements into account that contributed to these outcomes. The CROSS model helps to create the whole picture, for instance, by emphasising the different role of the physical and social environment, rather than focusing on a specific group or behaviour. It is important to be aware of the kind of physical context that individuals may find themselves in when in a crowd. Which information reaches the individual and may thus affect them? It becomes a strategic choice to make some attractions points 'invisible' in order to make sure that people do not start to hurry and push (e.g. when they see the stage of a festival while standing in a long queue). On the other hand, it could be a strategic choice to make certain attraction points 'visible' in order to put people in a more patient mode (e.g. information that the concert has not started yet). Following this reasoning will lead to (re)consider a number of choices in both the design of events and the management of crowds. In terms of the physical environment, it would be relevant to examine what is perceptually available to individuals before exploring potential influencing strategies. For one, the measures following from the strategies must reach the individuals involved, and secondly, the individuals must be able to act in the desired way (e.g. when it is too crowded, influences on movement are fruitless). In terms of the social context, it is important to know who one is dealing with, as influencing strategies must to 'fit' the setting. For example, when a crowd is directed in and out of a city in relation to an event, it makes a difference whether the guests know the city, in terms of how they let themselves be steered towards or away from points of interest. This thesis states clearly that it is not possible to draw conclusions on behaviour choices based on physical factors alone. This view directly contradicts a common view in the field of safety management. A recent example of this can be found in the emergency crowd example of the Love Parade in Duisburg, Germany (see chapter 1), where it was claimed that the catastrophe was the inevitable outcome of physical factors. The social context cannot be ignored.

8.3 Future

The results and conclusions of this thesis open the way for several exciting possibilities for future directions of both research and practice.

Research.

By developing, discussing and experimenting with the CROSS model new questions and topics that may give direction to future research for a further understanding of crowd behaviour will be generated:

Downward causation. The CROSS model represents crowd behavioural patterns as an emergent process. Group level patterns will arise bottom-up due to interactions between individuals. It would be interesting to explore the role of downward causation (i.e. top-down influence) in order to investigate the way group level patterns affect individuals. The dynamics between the cognitive, individual and group levels, the so-called micro-macro link (Sawyer, 2003; Gilbert, 2002) will increase the level of realism in modelling crowd behaviour. Another option would be to explore the impact of observing another group, for instance the the police, and study intergroup dynamics. Modern crowd research emphasises intergroup dynamics to explain escalation processes (Adang, 2010; Reicher, 2001). These concepts of 'in-group/out-group' and 'group membership' concepts invite to elaborate on the cognitive representation of groups, but also of the representation of oneself as a group member. In addition, the effects of feeling part of a group and perceiving another group can be explored, as well as how these notions change over time. Defining and integrating these concepts would initiate an important discussion on representing and combining these concepts, not only in crowd research, but also in the social and cognitive sciences. This is an intriguing area to enter, with a lot of open questions.

Experience and communication. Other paths worth pursuing, inspired by practical relevance, include the role of experience and communication. Experience, for example, can be related to normative behaviour at crowd events, or to the distinction between experts and non-experts in non-formal settings. Experience is in this sense related to what an agent considers 'normal behaviour' at such an event, based on its previous experiences. Including communication would allow to explore the influence of the local vicinity that is not restricted to spatial vicinity. The use of mobile phones is a good example of this. In this way, information could be explored as an intervention but also as a tool to coordinate or cooperate.

Behaviour variety. An increase in the amount of behaviours a CROSS agent could perform would be a relevant extension of the model. As a first step, it would be a good idea to provide a more realistic representation of the range of behaviours shown in real-life crowds by including behaviour that does not necessarily involve horizontal movement. The second improvement of the model would be to make the behaviour expectations dynamic. These expectations are crucial in selecting behaviour. However, currently, they are fixed. It would be interesting to have the expectations change on the basis of experiences over time, which would represent learning. For instance, learning that certain behaviour is more favourable in a certain a setting would give rise to norms. This way, personal preferences may arise, or normalised behaviour may form. The learning effect on expectations will provide important dynamics concerning the internal relevance of behaviour and thus of behavioural patterns at the group level. These suggestions have consequences. Adding an internal relationship, or dynamics to the behaviour expectations requires for theories or empirically based knowledge to incorporate or study the effect in such a way that it helps to understand crowd behaviour dynamics.

Emotions. A concept that is often mentioned when talking about crowd behaviour is emotion. It was briefly mentioned that a setting of the CROSS model, i.e. the internal state of an agent, could be interpreted as a reflection of emotion. Studies on emotion differ in the way they define emotion in terms of description level (intra-individual, inter-individual, group, culture) and perspective (evolutionary, social). The way emotion is defined has strong implications for the explanations that are provided. It would be a good idea to make an effort to clarify how emotion can be linked to the CROSS model.

Group measure for crowd behaviour patterns. In the CROSS model, behaviour clustering was used as a group measure. This measure represents behaviour patterns in a crowd, i.e. the identifiable subgroups that change over time. Currently, the measure does not represent the number of subgroups or the size of the subgroups. However, it might be interesting to distinguish between the different subgroups and to discern between subgroups on the basis of behaviour, size and changes in composition. This is, of course, inspired by the results of the leadership experiment, which showed the need for a measure that incorporates differences in behaviour. Naturally, this leads to the question of how to design a proper measure, what it does and does not represent, and to what extent it can be used for real crowds. Designing a group measure involves a theoretical, computational and practical debate.

Validation. The most important future direction concerns further validation of the CROSS model. In particular, its social and cognitive plausibility and the empirical validation of the CROSS model should be sought. Social and cognitive plausibility is emphasised as the description of the individual's internal world must be grounded. The use of a structure and the way knowledge is represented in memory is adopted from a cognitively plausible architecture. However, at present, not everything can be grounded. For instance, the way in which memory elements represent and change the social world due to the interaction with the world concerns an assumption that has not been empirically tested. Further research in both the cognitive and the social sciences is needed to develop these kinds of models. The second validation need concerns closing the empirical loop to real-world conclusions. A combination of empirical and simulation studies would foster further understanding by making empirical data available for setting and validating simulations. Combining the two would also allow to conduct specific empirical studies based on the insights gained from simulation results. For example, the measure of behaviour clustering is developed in such a way that it can function as a measure in real crowds. Gathering data of crowds with varying density levels at a festival would supply input to further validate the CROSS model. In addition, observational studies could be conducted that incorporate this 'complete-picture approach', where both physical and social factors would be registered and systematically compared.

Practice.

Crowd research has an obvious link to reality and the knowledge generated by crowd research can be and is being used in practice, e.g. to assist in training, event preparations or decision-making processes. This thesis addresses fundamental questions and theories concerning crowd behaviour, which are however, still standing far from practice. Nevertheless, the possibilities for future usability are obvious. From a practical perspective, it would be particularly relevant to explore those crowd phenomena that are also interesting for LEOs. In addition to generating relevant knowledge, the use the simulation of crowd behaviour has other potential uses for practitioners.

Visualising theory. The CROSS model is already capable of visualising a theory and shows what happens in a crowd. In this way, practitioners may be confronted with the current state of knowledge in a more accessible form than when they are provided with books or given lectures. A simulation enables to get a feeling of what happens. A theory can be rather complex to explain, especially due to the dynamics in crowds. It may be grasped more easily when visualised.

Training. LEOs usually receive a special training to deal with crowds. Actually dealing with crowds is where the LEOs gain their real experience. The use of a simulation training tool or Virtual Reality (VR) could provide LEOs with another, flexible, option to gain more experience. A tool for training requires further development of the CROSS model, but first of all it requires more fundamental knowledge of crowd behaviour, more than is available right now. In the CROSS model more scenarios should be developed, with behaviour being more closely related to reality. To support learning, a tutor system behind the screens should be developed as well.

Decision support Another type of system that could in principle be developed from a model like the CROSS model is a decision support system for crowd management. Such a system could support strategic decision making when preparing for crowd events. An application could help ensure that all relevant questions are addressed in the preparation of an event. Another application could make clear what the consequences of these decisions are. These applications are part of the distant future, as they require fundamental knowledge of crowd behaviour, but also general knowledge about behaviour itself and especially specific context-related knowledge in terms of scenarios.

Bibliography

Jade.. http://jade.tilab.com.

Mason.. http://cs.gmu.edu/ eclab/projects/mason/.

Netlogo.. http://ccl.northwestern.edu/netlogo/.

Recusive Porous Agent Simulation Toolkit (Repast).. http://repast.sourceforge.net.

Abbott, A. (2003). *Methods of Discovery*. W.W. Norton & Company.

Adang, O. (1990). *Geweld en politie-optreden*. Universiteit Utrecht.

Adang, O. (1991). *Agressie*, chap. Gedrag van mensen tijdens rellen. Van Gorcum.

Adang, O. (1998). *Hooligans, autonomen, agenten. Geweld en politie-optreden in relsituaties*. Samson. English summary: http://policestudies.homestead.com/riots.html.

Adang, O. (2006). *Het beste politiekorps van de hele wereld: Met alle geweld leren...* Police Academy, Apeldoorn, The Netherlands.

Adang, O. M. J. (2010). *Preventing Crowd Violence*, chap. Initiation and escalation of collective violence: a comparative observational study of protest and football events. Criminal Justice Press. In press.

Allport, F. H. (1924). *Social Psychology*. Houghton Mifflin.

Altmann, E. M. (2007). *Integrated Models of Cognitive Systems*, chap. Control Signals and Goal-Directed Behavior, pp. 380–387. Oxford University Press. H26.

Aminzade, R., & McAdam, D. (2002). Emotions and Contentious Politics. *Mobilization*, *7*, 107–109.

Anderson, C. A., Bushman, B. J., & Groom, R. W. (1997). Hot years and serious and deadly assaults: Empirical tests of the heat hypothesis. *Journal of Personality and Social Psychology*, *78*, 1213–1223.

Anderson, C. A., & Anderson, K. B. (1998). *Human aggression: Theories, research and implications for social policy.*, chap. Temperature and aggression: Paradox, controversy, and a (fairly) clear picture., pp. 247–298. San Diego, Academic Press.

Anderson, J. R. (2007). *How Can the Human Mind Occur in the Physical Universe*. Oxford University Press.

Anderson, J. R., & Lebiere, C. (1998). *The atomic components of thought*. Lawrence Erlbaum Associates.

Arts, N., van Leiden, I., & Ferwerda, H. (2009). *Rellen om te rellen*. Reed business.

Aveni, A. (1977). The not-so-lonely Crowd: Friendship groups in collective behavior. *Sociometry*, *40*, 96–99.

Balci, O. (1998). *Handbook of Simulation*, chap. 10. Verification, Validation, and Testing, pp. 335–396. John Wiley & Sons.

Ballard, D., & Sprague, N. (2007). *Integrated Models of Cognitive Systems*, chap. On the Role of Embodiment in Modeling Natural Behaviours, pp. 283–296. Oxford University Press.

Baron, R. A., & Richardson, D. R. (1994). *Human Aggression*. Plenum Press.

Baron, R. R., & Kerr, N. L. (Eds.). (2003). *Group process, group decision, group action* (Second edition). Open University Press.

Barrow, J. C. (1977). The Variables of Leadership: A Review and Conceptual Framework. *The Academy of Management Review*, *2*(2), 231 – 251.

Baumeister, R. F. (1998). *Handbook of Social Psychology* (4th edition)., chap. The Self, pp. 680–740. Mc graw-Hill, New York.

Berk, R. (1972a). *Collective Violence*, chap. The Controversy Surrounding Analyses of Collective Violence: Some Methodological Notes, pp. 309–329. Chicago: Aldine.

Berk, R. (1972b). *Collective Violence*, chap. The Emergence of Muted Violence in Crowd Behavior: A Case Study of an Almost Race Riot, pp. 112–118. Chicago: Aldine.

Berk, R. (1974a). *Collective Behavior*. Wm.

Berk, R. (1974b). A Gaming Approach to Crowd Behavior. *American Sociological Review*, *39*, 355–373.

Berkowitz, L. (1981). *Multidisciplinary approaches to aggression research*, chap. The concept of aggression, pp. 3–15. Orlando FL : Academic Press.

Berkowitz, L. (1988). Frustrations, appraisals, and aversively stimulated aggression. *Aggressive Behavior*, *14*, 3–11.

Bitting, E., Carter, J., & Ghorbani, A. A. (2003). Multiagent Systems Development Kits: An Evaluation. In *Proceedings of the 1st Annual Conference on Communication Networks & Services Research*.

Boden, M. A. (2008). *The Cambridge handbook of computational psychology*, chap. An Evaluation of Computational Modeling in Cognitive Science, pp. pp 667–683. Cambridge University Press.

Brooks, R. A. (1991). Intelligence without representation. *Artificial Intelligence*, *47*, 139–159.

Brown, R. (2000). *Group processes: dynamics within and between groups* (Second edition).

Bruinsma-Jakobsen, S. (2007). Interaction between crowd and police: effects of anonymity, expectations, and arousal on police use of force. Master's thesis, University of Leiden.

Bryman, A. (1992). *Charisma & leadership in organizations*. Sage Publications.

Burton, I., Kates, R., & White, G. (1993). *The environment as Hazard*, Vol. second edition. The guilford Press, New York.

Cannavale, F., Scarr, H., & Pepitone, A. (1970). De-individuation in the small group: Further evidence. *Journal of Personality and Social Psychology*, *16*, 141–147.

Carley, K., & Newell, A. (1994). The Nature of the social agent. *Journal of mathematical sociology*, *19*(4), 221–262.

Carlson, R. A. (2007). *Integrated Models of Cognitive Systems*, chap. Intentions, Error, and Experience, pp. 388–399. Oxford University Press. H27.

Castelfranchi, C. (1995). *Intelligent Agents: Theories, Architectures and Languages:*, Vol. 890 of *Lecture notes in computer science, ISSN 0302-9743*, chap. Guarantees for autnomy in cognitive agent architecture, pp. 56–70. Springer Berlin / Heidelberg.

Challenger, R., Clegg, C. W., & Robinson, M. A. (2009a). Simulation Tools. In Leigh, M. (Ed.), *Understanding Crowd Behaviours*. Crown.

Challenger, R., Clegg, C. W., & Robinson, M. A. (2009b). Supporting Evidence. In Leigh, M. (Ed.), *Understanding Crowd Behaviours*. Crown.

Challenger, R., Clegg, C. W., & Robinson, M. A. (2009c). *Understanding Crowd Behaviours*. Crown.

Charry, J. M., & Hawkinshire, F. B. W. (1981). Effects of atmosferic electricity on some substrates of disordered social behavior. *Journal of Personality and Social Psychology*, *41*, 185–197.

Cialdini, R. B., Reno, R. R., & Kallgren, C. A. (1990). A Focus Theory of Normative Conduct: Recycling the Concept of Norms to Reduce Littering in Public Places. *Journal of Personality and Social Psychology*, *58*(6), 1015–1026.

Cottrell, J. L. (1972). *Experimental Social Psychology*, chap. Social facilitation. Holt.

Couch, C. J. (1968). Collective Behavior: An Examination of Some Stereotypes. *Social Problems*, *15*(3), 310–322. ISSN = 00377791.

Damasio, A. (1994). *Descartes' Error: Emotion, Reason, and the Human Brain*. New York: Putnam.

Dennet, D. C. (1978). *Brainstorms, Philosophical Essays on mind an Psychology*, chap. Intentional systems, pp. 3–22. The Harvester Press Limited.

Dettweiler, M. (2010). Augenzeugenbericht von der Loveparade. Warum nur diese Polizeikette?. Website. http://www.faz.net/-01e66c.

Diener, E. (1976). Effects of prior destructive behavior, anonymity, and group presence on deindividuation and aggression. *Journal of Personality and Social Psychology*, *33*, 497–507.

Diener, E. (1977). Deindividuation: Causes and consequences.. *Social Behaviour and Personality*, *5*, 143–155.

Diener, E. (1980). *The psychology of group influence*, Vol. 5, chap. Deindividuation: The absence of self-awareness and self-regulation in group members., pp. 143–155. Hillsdale, NJ: Erlbaum.

Drury, J., & Reicher, S. (1999). The intergroup dynamics of collective empowerment: Substantiating the social identity model of crowd behavior.. *Group Processes & Intergroup Relations*, *2*, 381–402.

Drury., J., & Reicher, S. (2000). Collective action and psychological change: The emergence of new social identities.. *British Journal of Social Psychology*, *39*, 579–604.

Drury, J., & Reicher, S. (2005). Explaining enduring empowerment: A comparative study of collective action and psychological outcomes.. *European Journal of Social Psychology*, *35*, 35–58.

Eisinger, P. K. (1973). The Conditions of Protest Behavior in American Cities. *The American Political Science Review*, *67*(1), 11–28.

Epstein, J. (2002). Modeling Civil Violence: An Agent-Based Computational Approach. In *Proceedings of the National Academy of Sciences*.

Feinberg, W. E., & Johnson, N. R. (1988). "Outside Agitators" and Crowds: Results from a Computer Simulation Model. *Social Forces*, *67*(2), 398–423.

Festinger, L., Pepitone, A., & Newcomb, T. (1952). Some consequences of deindividuation in a group. *Journal of Abnormal and Social psychology*, *47*, 382–389.

Fiske, & Taylor (1991). *Social cognition* (Second edition). New York, McGraw Hill.

Forsyth, R. D. (2006). *Group Dynamics* (Fourth edition). Thomson Wadsworth.

Franklin, S., & Graesser, A. (1996). Is it an Agent, or just a Program? A Taxonomy for Autonomous Agents. In *Third International Workshop on Agent Theories, Architectures, and Languages*.

Freedman, J. L. (1975). *Crowding and behavior*. W.H.Freeman & Co.

Freedman, J. L., Birsky, J., & Cavoukian, A. (1980). Environmental Determinants of Behavioral Contagion: Density and Number. *Basic and Applied Social Psychology*, *1*(2), 155–161.

Fridman, N., & Kaminka, G. A. (2009). Comparing Human and Synthetic Group Behaviors: AModel Based on Social Psychology. In *International Conference on Cognitive Modeling (ICCM-09)*. A previous version of this paper appeared in the proceedings of the Multi-Agent Based Simulation (MABS) workshop at AAMAS-2009.

Fruin, J. (1985). Crowd dynamics and the design and management of public places.. In Pauls, J. (Ed.), *Int. Conf. on Building Use and Safety Technology*, pp. 110–113 Washington DC. National Institute of Building Sciences.

Fruin, J. J. (1971). *Pedestrian Planning and Design.* Metropolitan Association of Urban Designers and Environmental Planners.

Gazendam, H., & Jorna, R. J. (1998). Theories about Architecture and Performance of Multi-agent Systems. SOM Research Report 98 A02.

Geen, R. G., & O'Neal, E. C. (1969). Activation of cue-elicited aggression by general arousal. *Journal of Personality and Social Psychology*, *11*, 289–292.

Gilbert, N. (2002). Varieties of Emergence. Transcript of the introductory talk given at the Workshop on Agent 2002 Social Agents at the Ecology, Exchange, and Evolution Conference 2002.

Gilbert, N., & Troitzsch, K. G. (2005). *Simulation for the social scientist* (2 edition). Open university Press. ISBN: 0335216005.

Goodwin, J., Jasper, J. M., & Polletta, F. (Eds.). (2001). *Passionate politics: emotions and social movements*, chap. Why Emotions Matter, pp. 1–24. The university of Chicago.

Granovetter, M. (1978). Threshold Models of Collective Behavior. *The American Journal of Sociology*, *83*(6), 1420–1443.

Gray, W. D. (Ed.). (2007). *Integrated Models of Cognitive Systems*. Oxford University Press.

Groot, A. D. (1961). *Methodologie, grondslagen van onderzoek en denken in de gedragswetenschappen*. Uitgeverij Mouton, 's Gravenhage.

Gross, E. (1990). *Getting the world to the people*, chap. X. Natural Disaster Management.

Haak, A. J. H., & van der Burgh, L. (1994). *De menselijke maat*. Delftse universitaire pers.

Harrington, J. (1968). *Soccer Hooliganism.* Bristol: John Wright.

Helbing, D., Buzna, L., Johansson, A., & Werner, T. (2005). Self-Organized Pedestrian Crowd Dynamics: Experiments, simulations, and Design Solutions. *Transportation Science*, *39*(1), 1–24.

Helbing, D., Farkas, I., & Vicsek, T. (2000). Simulating dynamical features of escape panic. *Nature*, *407*, 487–490.

Helmhout, M. (2006). *The Social Cognitive Actor, A multi-actor simulation of organizations*. Ph.D. thesis, University of Groningen.

Hendriks, P., Taatgen, N., & Andringa, T. (1997). *Breinmakers & Breinbrekers*. Addison Wesley Longman.

Hewstone, M., & Stroebe, W. (Eds.). (2001). *Social Psychology. A European Perspective.* (Third edition). Blackwell Publishing.

Hofling, C. K., Brotzman, E., Dalrymple, S., Graves, N., & Pierce, C. M. (1966). An experimental study in nurse-physician relationships. *Journal of Nervous and Mental Disease*, *143*, 171–180.

Hogg, M. A., & Vaughan, G. M. (2008). *Social psychology*. Pearson Educated Limited.

Hollander, E. (1985). *Leadership and power* (3rd edition)., Vol. 2, pp. 485–537. Random House, New York.

Hollander, E. (1993). *Legitimacy, power, and influence: A perspective on relational features of leadership*, pp. 29–47. Academic Press, San Diego.

Hollander, E., & Offermann, L. (1990). Power and leadership in organizations: Relationships in transition. *American Psychologist*, *45*, 179–189.

Humphreys, P. (2006). *Encyclopedia of Philosophy*, Vol. 2nd ed., chap. Emergence, pp. 190–194. Macmillan Reference USA.

Jager, W. (2000). *Modelling Consumer Behaviour*. Ph.D. thesis, University of Groningen.

Jager, W., Popping, R., & van de Sande, H. (2001). Clustering and Fighting in Two-party Crowds: Simulating the Approach-avoidance Conflict. *Journal of Artificial Societies and Social Simulation*, *4*(3).

Jennings, N. R., Sycara, K., & Wooldrigde, M. (1998). A Roadmap of Agent Research and Development. *Autonomous Agents and Multi-agent systems*, *1*, 7–38.

Johnson, N. R., & Feinberg, W. E. (1977). A Computer Simulation of the Emergence of Consensus in Crowds. *American Sociological Review*, *42*(3), 505–521.

Jorna, R. (2000). *De 'zwarte doos' in de bedrijfskunde: cognitie in actie*. University of Groningen.

Kalat, J. W. (2001). *Biological psychology* (7th edition). Wadsworth.

Kaldor, N. (1961). *The Theory of Capital*, chap. Capital Accumulation and Economic Growth, pp. 177–222. St. Martins Press.

Kallgren, C. A., Reno, R. R., & Cialdini, R. B. (2000). A Focus Theory of Normative Conduct: When Norms Do and Do Not Affect Behavior. *Society for Personality and Social psychology*, *26*(8), 1002–1012.

Kemp, C., Hill, I., & Upton, M. (2004). *A Comparative Study of Crowd Behaviour at Two Major Music Events*. Entertainment Technology Press.

Kemp, C., Hill, I., Upton, M., & Hamilton, M. (2007). *Case studies in crowd management*. Entertainment Technology Press.

Kendrick, Neuberg, & Cialdini (2005). *Social Psychology*. Referentie nog volledig maken.

Krahé, B. (2001). *The social psychology of aggression*. Psychology Press.

Law, A. M. (2007). *SimulationModeling and Analysis* (Fourth edition). Mc Graw Hill.

LeBon, G. (1895). *La Psychologie des Foules*. Alcan.

Leibman, M. (1970). The Effects of Sex and Race Norms on Personal Space. *Environment and Behavior*, *2*(2), 208–246.

Lindblom, J., & Ziemke, T. (2002). Social Situatedness: Vygotsky and Beyond..

Lofland, J. (1985). *Protest: Studies of Collective Behavior and Social Movements:*. NJ: Transaction Books.

Maslow, A. (1943). A theory of human motivation. *Psychological Review*, *50*, 370–396.

Massey, D. S. (2002). A Brief History of Human Society: The Origin and Role of Emotion in Social Life.. *American Sociological Review*, *67*, 1–29.

Max-Neef, M. (1993). *Real-life economics: Understanding wealth creation*, chap. Development and human needs, p. 197.

McPhail, C. (1991). *The myth of the madding crowd*. Aldine de gruyter.

McPhail, C. (1994). Presidential Address THE DARK SIDE OF PURPOSE: Individual and Collective Violence in Riots. *The Sociological Quarterly*, *35*(1), 1–32. ISSN: 0038-0253.

Milgram, S. (1970). The Experience of Living in Cities. *Science*, *167*(3924), 1461–1468. ISSN = 00368075.

Milgram, S. (1974). *Obedience to Authority*. Harper.

Miller, N., & Dollard, J. (1941). *Social Learning and Imitation*. Yale University Press.

Mosler, H.-J., & Schwarz, G. (2005). Investigating Escalation Processes in Peace Support Operations: An Agent-based Model about Collective Aggression. In Troitsch, K. G. (Ed.), *Representing Social Reality*, pp. 191–197. European Social Simulation Association, Verlag Dietmar Fölbach.

Mulder, M. (1977). *Omgaan met macht: Ons gedrag met elkaar en tegen elkaar*. Elsevier.

Mullen, B., Migdal, M. J., & Rozell, D. (2003). Self-Awareness, Deindividuation, and Social Identity: Unraveling Theoretical Paradoxes by Filling Empirical Lacunae. *Society for Personality and Social Psychology*, *29*(9), 1071–1081.

Muller, E., Rosenthal, U., Zannoni, M., Ferwerda, H., & Schaap, S. D. (2009). Strandrellen in Hoek van Holland, Dancefestival Veronica SunsetGrooves, 22 augustus 2009. Report.

Musse, S. R., & Thalmann, D. (1997). A Model of Human Crowd Behavior: Group Inter-Relationship and collision Detection Analysis. In *Computer Animatioin and Simulation '97, Proc. Eurograpics workshop*, pp. 39–51 Budapest. Springer Verlag.

Musse, S., & Thalmann, D. (2001). A behavioral model for real time simulation of virtual human crowds. *IEEE Transactions on Visualization and Computer Graphics*, *7*(2), 152–164.

Neal, D. M. (1994). A Further Examination of Anonymity, Contagion, and Deindividuation in Crowd and Collective Behavior.. *Sociological Focus*, *26*, 93–107.

Newell, A. (1982). The Knowledge Level. *Artificial Intelligence*, *18*(1), 87–127.

Newell, A. (1990). *Unified theories of cognition*, Vol. 3. Harvard University Press.

Nguyen, Q.-A., McKenzie, F. D., & Petty, M. D. (2005). Crowd Behavior Cognitive Model Architecture Design. In *Proceedings of the 2005 Conference on Behavior Representation in Modeling and Simulation*.

Nikolai, C., & Madey, G. (2009). Tools of the Trade: A Survey of Various Agent Based Modeling Platform. *Journal of Artificial Societies and Social Simulation*, *12*(2).

Northouse, P. G. (2004). *Leadership: theory and practice* (Third edition). Sage Publications.

Otten, M., Boin, R., & van der Torre, E. (2001). *Dynamics of Disorder: Lessons from Two Dutch Riots*. The Hague Crises Center, Leiden University.

Park, R. E. (1904). *Masse und Publikum*. Bern: Lack and Grunau. English translation by Charlotte Elsner (1982), edited by Henry Elsner. The Crowd and the Public. Chicago: University of Chicago Press.

Patten, S. B., & Arboleda-Flórez, J. A. (2004). Epidemic theory and group violence. *Social Psychiatry and Psychiatric Epidemiology*, *39*(11), 853–856.

Patterson, M. L., Mullens, S., & Romano, J. (1971). Compensatory Reactions to Spatial Intrusion. *Sociometry*, *34*(1), 114–121.

Pavlov, I. P. (1927). *Conditioned Reflexes: An Investigation of the Physiological Activity of the Cerebral Cortex*. London: Oxford University Press.

Petrov, A. A. (2006). Computationally Efficient Approximation of the Base-Level Learning Equation in ACT-R. In D. Fum, F. del Missier, . A. S. (Ed.), *In Proceedings of the Seventh International Conference on Cognitive Modeling*, pp. 391–392.

Pfeifer, R., & Scheier, C. (1999). *Understanding intelligence*. The MIT Press.

Posner, M. (Ed.). (1989). *The Foundations of Cognitive Science*. The MIT Press.

Postmes, T., Spears, R., & Lea, M. (1998). Deindividuation and antinormative behavior: A meta-analysis.. *Psychological Bulletin*, *123*(3), 238–259.

Prentice-Dunn, S., & Rogers, R. W. (1989). *The psychology of group influence*, chap. Deindividuation and the self-regulation of behavior., pp. 62–89. Hillsdale, NJ: Erlbaum.

Purdom, J. (1990). *Monitoring and Forecasting*, chap. VII. Natural Disaster Management.

Reicher, S. (1996). The battle of WestminsterŠ: developing the social identity model of crowd behaviour in order to explain the initiation and development. *European Journal of Social Psychology*, *26*, 115–134.

Reicher, S., & Levine, M. (1994). Deindividuation, power relations between groups and the expression of social identity: The effects of visibility to the outgroup. *British Journal of Social Psychology*, *33*, 145–163.

Reicher, S. D. (1997). Collective psychology and the psychology of the self.. *BPS Social Section Newsletter*, *36*, 3–15.

Reicher, S. (2001). *Blackwell Handbook of Social Psychology: Group Processes*, chap. The Psychology of Crowd Dynamics, pp. 182–208. Blackwell Publishers.

Reynolds, C. W. (1987). Flocks, Herds, and Schools: A Distributed Behavioral Model. *Computer Graphics*, *21*(4), 25–34. (SIGGRAPH'87 Conference Proceedings).

Rotten, J. F., Barry, T., Milligan, M., & Fitzpatrick, M. (1979). The air pollution experience and physical aggression. *Journal of Applied Social Psychology*, *9*, 387–412.

Russel, G. W. (1993). *The social psychology of sport*. Springer.

Sanbonmatsu, D. M., & Kardes, F. R. (1988). The Effects of Physiological Arousal on Information Processing and Persuasion. *The Journal of Consumer Research*, *15*(3), 379–385.

Sanders, G. S., Baron, R. S., & Moore, D. L. (1978). Distraction and social comparison as mediators of social facilitation effects. *Journal of Experimental Social Psychology*, *14*, 291–303.

Sargent, R. G. (2000). Verification, validation, and accreditation of simulation models. In Joines, J. A., Barton, R. R., Kang, K., & Fishwick, P. (Eds.), *Proceedings of the 2000 winter Simulation Conference*.

Sawyer, R. K. (2003). Artificial Societies Multiagent Systems and the Micro-Macro Link in Sociological Theory. *Sociological methods & Research*, *31*(3), 325–363.

Schelling, T. C. (1971). Dynamic models of segregation. *Journal of Mathematical Sociology*, *1*, 143–186.

Schreiber, M., & Adang, O. (2008a). Schwarze Blöcke und blau/grüne Massname-Über Gewalt bei Grossereignissen und die Rolle der Polizei. *Die Polizei*, *12*, 346–350.

Schreiber, M., & Adang, O. (2008b). Wissenschaft und Polizeipraxis: Die Untersuchung von Einsätzen bei sportlichen Grossereignissen. *Die neuen Polizei*, *1*, 3–8.

Schreiber, M. (2010). *Group relations at crowd events*. Ph.D. thesis, Jacobs university Bremen.

Schweingruber, D., & Wohlstein, R. T. (2005). The madding crowd goes to school: myths about crowds in introductory sociology textboooks. *Teaching Sociology Compass*, *33*, 136–153.

Schweizer-Ries, P., & Fuhrer, U. (2006). *Handbuch der Sozialpsychologie und Kommunikationspsychologie*, chap. Crowding, pp. 777–783. Göttingen: Hogrefe. ISBN 3-8017-1844-1.

Severy, L. J. (1978). Crowding, theoretical & research Implications for population-environment psychology. *Journal of Population*, *1*(3), 189–279.

Shah, J. Y. (2005). The Automatic Pursuit and Management of Goals. *American Psychological society*, *14*(1), 10–13.

Shakshuki, E., & Jun, Y. (2004). Multi-agent Development Toolkits: An Evaluation. *Lecture notes in computer science*, *3029*, 209–218.

Silverman, B. G., Johns, M., Weaver, R., O'Brien, K., & Silverman, R. (2002). Human Behavior Models for Game-Theoretic Agents: Case of Crowd Tipping. *Cognitive Science Quarterly*, *2*(3/4).

Sime, J. D. (1995). Crowd psychology and engineering. *Safety Science*, *21*, 1–14.

Simon, H. A. (1957). *Models of Man, Social and Rational: Mathematical Essays on Rational Human Behavior in a Social Setting*. John Wiley and Sons, Inc.

Simon, H. A. (1996). *The sciences of the Artificial* (Third edition). The MIT Press. ISBN 0-262-19374-4.

Stapel, D. A., & van der Zee, K. I. (2006). The Self Salience Model of Other-to-Self Effects: Integrating Principles of Self-Enhancement, Complementarity and Imitation. *Journal of Personality and Social Psychology*, *90*(2), 258–271. Gebruikt voor het vak: Cognitie, Motivatie en Emotie.

Still, K. (2000). *Crowd Dynamics*. Ph.D. thesis, University of Warwick.

Stockdale, J. E., Wittman, L. S., Jones, L. E., & Greaves, D. A. (1978). Conceptual Dimension of Crowding: A London (England) Study. *Journal of Population*, *1*(3), 239–250.

Stott, C., Adang, O., Livingstone, A., & Schreiber, M. (2007). Variability in the collective behaviour of England fans at Euro2004: ŚHooliganismŠ, public order policing and social change.. *European Journal of Social Psychology*, *37*, 75–100.

Stott, C., Adang, O., Livingstone, A., & Schreiber, M. (2008). Tackling football hooliganism: A quantitative study of public order, policing and crowd psychology.. *Psychology, Public Policy and Law*, *14*, 115–141.

Stott, C., & Drury, J. (1999). *Transforming Politics:Power and Resistance*, chap. The intergroup dynamics of empowerment: A social identity model., pp. 32–45. London: Macmillan.

Stott, C., & Reicher, S. (1998). How conflicts escalates: the inter-group dynamics of collective football crowd violence. *Sociology*, *32*, 353–377.

Stott, C., & Drury, J. (2000). Crowds, context and identity: dynamic categorization processes in the 'poll tax riot'. *Human Relations*, *53*(2), 247–273.

Sun, R. (2000). Cognitive Science Meets Multi-agent Systems: A Prolegomenon. *Philosophical Psychology*, *14*(1), 5–29.

Sun, R. (2003). A Tutorial on CLARION 5.0. Tech. rep..

Sun, R. (2008). *The Cambridge Handbook of Computational Psychology*, chap. Cognitive Social Simulation, pp. 530–548. Cambridge University Press.

Tajfel, H. (1981). *Human groups and social categories: Studies in social psychology*. Cambridge University Press.

Tarnow, E. (1996). Like Water and Vapor–conformity and Independence in the Large Group. *Behavioral Science*, *41*, 136–151.

Team, L. P. (2010). Dokumentation Loveparade 24.7.2010. Website. http://www.dokumentation-loveparade.com/.

Thagard, P., & Verbeurgt, K. (1998). Coherence as constraint satisfaction. *Cognitive Science*, *22*, 1–24.

Therakomen, P. (2001). The Experiments for Exploring Dynamic Behaviors in Urban Places. Master's thesis, University of Washington.

T.Horlick-Jones, & Jones, D. (1993). *Communicating risks to reduce vulnerability*, chap. X, pp. 25–37. Natural Disasters.

Tucker, C., Schweingruber, D., & McPhail, C. (1999). Simulating Arcs and Rings in Gatherings. *International Journal of Human-Computer Studies*, *50*, 581–588.

Turner, J., Oakes, P., Haslam, S., & McGarty, C. (1994). Self and collective: Cognition and social context.. *Personality and Social Psychology Bulletin*, *20*, 454–463.

Turner, R., & Killian, L. (1987). *Collective Behavior* (Third edition). NJ: Prentice-Hall.

van de Sande, H. (2006). *On Crowds*.

van den Brug, H. (1986). *Voetbalvandalisme, een speurtocht naar verklarende factoren.* De Vrieseborch, Haarlem.

van der Valk, P., & Linckens, P. (1988). Voetbalvandalen: hun contacten met politie en Justitie.. *Tijdschrift voor Criminologie*, *4*, 313–320.

van Vliet, T., & de Bruin, R. (2007). Enhancing peace keeping operations with NLWs. In *Non-Lethal Weapons: Fulfilling the Promise?* Ettlingen, Germany. 4th European Symposium on Non-Lethal Weapons, Fraunhofer Institut für Chemische Technologie.

Waddington, D., Jones, K., & Critcher, C. (1989). *Flashpoints: studies in public order*. London: Routledge.

Waddington, D. P. (2007). *Policing Public Disorder: Theory and Practice*. Devon: Willan Publishing.

Wahba, M. A., & Bridwell, L. G. (1976). Maslow reconsidered: A review on the need hierarchy theory. *Organizational behavior and human performance*, *15*, 212–240.

Wanders, J. (2009). Het aantal hooligans groeit en groeit. Newspaper: Volkskrant.

Watson, J. B. (1930). *Behaviorism.* (Revised edition). University of Chicago Press.

WDR (2010a). 21 Tote bei der Loveparade 2010 in Duisburg Die Ereignisse von Samstag und Sonntag. Website. http://www.wdr.de/themen/panorama/loveparade_2010/unglueck/100726_chronik.jhtml.

WDR (2010b). Ermittlungen der Staatsanwaltschaft wegen fahrlässiger Tötung auf Loveparade. Newspaper: WDR.

Weidmann, U. (1993). *Transporttechnik der Fussgänger, Transporttechnische Eigenschaften des Fussgängerverkehrs.*, Vol. 2. IVT Istitut für verkehrsplanung.

Wetzer, I., Kamphuis, W., van Hemert, D., in 't Veld, M. H., & Kerstholt, J. (2010). Gedrag onder invloed van niet-letale middelen: twee veldexperimenten (Behaviour under the influence of non-lethal weapons: two field experiments). Confidential report (10 years).

Wiekens, C. J., & Stapel, D. A. (2003). De spiegel en ik. Over de effecten van verschillende zelfbewustzijnmanipulaties op stereotypering. *Jaarboek Social Psychologie*.

Wijermans, N., Jorna, R., Jager, W., & van Vliet, T. (2007). Modelling Crowd dynamics. Influence factors related to the probability of a riot. In Amblard, F. (Ed.), *Proceedings of ESSA'07 the 4th Conference of the European Social Simulation Association*. IRIT Editions.

Wijermans, N., Jorna, R., Jager, W., & van Vliet, T. (2008). Modelling the Dynamics of Motivational and Situated behaviour. In *Proceedings of the 2nd World World Congress on Social Simulation*. George Mason University.

Wilson, M., & Daly, M. (1985). Competitiveness, risk-taking and violence: the young mail syndrome. *Ethology and Sociobiology*, *6*, 59–73.

Wilson, R. A., & Keil, F. C. (Eds.). (1999). *The MIT Encyclopedia of The Cognitive Science*. The MIT Press.

Wooldridge, M., & Jennings, N. (1995). Intelligent agents: Theory and practice. *The Knowledge Engineering Review*, *10*(2), 115–152.

Wooldridge, M. J. (2002). *An introduction in Multi-agent systems*. John Wiley & Sons Ltd. ISBN 048149691.

Zajonc (1980). *Psychology of Group Influence* (Second edition)., chap. Compresence. Lawrence Erlbaum Associates.

Zillmann, D. (1988). Cognitive-excitation interdependencies in aggressive behavior. *Aggressive Behavior*, *14*, 51–64.

Zimbardo, P. G. (1969). The human choice: Individuation, reason and order versus deindividuation, impulse, and chaos.. In Arnold, W. J., & Levine, D. (Eds.), *Nebraska symposium on motivation: 1969.*, No. 17, pp. 237–307 Lincoln, NE. University of Nebraska Press.

Summary

This thesis seeks to answer the question:

> Which mechanisms underlie crowd behaviour patterns?

As a first step in the process to find an explanation for the mechanisms that underlie behaviour patterns, literature will be studied (chapter 2). There exists a lot of literature on crowd phenomena, mainly from a practical perspective. Practitioners are experience-driven and only rarely act in a way that is informed by the latest results of crowd research. At the same time, however, science often does not provide the systematic knowledge that practitioners need, in spite of the existing body of crowd research. Modern crowd research provides empirically-based description of crowd behaviour. Altogether, these studies identify a number of influence factors that are supposedly relevant for crowd behaviour (e.g. density, power structure). However, studies that describe *why* and *how* these factors exert their supposed effects remain scarce. The explanations provided so far tend to apply only in specific types of situations, predominantly disorder or emergency situations. Disorder studies focus on explanations in the social context, whereas emergency studies focus on explanations in the physical context. Nevertheless, three important general insights can be drawn from modern crowd research:

- Crowd behaviour is generated by individuals, i.e. agency is at the individual level (and not at the group level).
- Crowd behaviour is context dependent (context includes both the physical and social environment).
- Crowd behaviour is dynamic: there is a continuous interaction between individuals and the environment over time.

Given these insights, one cannot help but notice that the provided explanations do not incorporate the way in which individuals process information and choose behaviour. Consequently, reference to theories from cognitive sciences is rarely made in crowd research.

Given the current state of knowledge and the fact that controlled experiments on crowds cannot be performed, two research needs are identified: First, the need for a theoretical model that reflects the dynamic interplay between individuals and their environment and second, the need for a method that allows for testing this theory. The development of the crowd model CROSS satisfies these two requirements.

CROSS represents a theory of crowd behaviour that is subsequently explored in simulation experiments.

CROSS is developed based on an integrative, multi-level and situated approach. The model is integrative, as relevant knowledge from the social and cognitive sciences is integrated into a common framework. The model has multiple levels, the group level at which behaviour patterns emerge, the individual level on which behaviour is generated and the cognitive level at which behaviour is affected. The model is situated, because individuals are embodied (the physical aspect of having a body) and embedded (the mental state related to current context and experience). CROSS thus incorporates the three main insights from modern crowd research and advances it by adding a description of behaviour at the cognitive (intra-individual) level. The cognitive level reflects the view of individuals as human information processing systems (cognitive systems) (chapter 3). This integrative, multi-level and situated approach of CROSS leads to detailed explanations. It forces explicitness when incorporating theories and concepts that makes them more concrete and precise. The model demands a specification of crowd behaviour that includes the way individual behaviour is affected and generated; a specification of what it means to have a body and to be embedded; what it means to be placed in a physical and social context; and lastly, a specification of how these aspects co-evolve over time. Furthermore, the model supports the incorporation of any number of additional factors, ideas and theories considered relevant. In this way, the model facilitates a multi-disciplinary and integrative approach.

To test and study the model, simulation is the chosen method. Simulation provides both experimental freedom and a rigid scientific structure, thereby addressing exactly the current needs of crowd research. Existing models could not be adopted as they were either too simplistic to represent general crowd behaviour, too specifically focused on a certain type of behaviour, or did not incorporate the modern foundations of crowd research. The design approach chosen to represent CROSS in a computational form is a multi-agent system. Multi-agent systems allow for the incorporation of all required elements: the multiple levels, the individual level richness (cognitive level) and the role of context and the overall dynamics. To be able to perform experiments, the theoretical model is formalised into a computational model. For this step, each concept and relation needed to be defined in computer-understandable variable or method. Formalisation is an important step that involves the use of existing knowledge or data and a creative approach for being able to transfer the theoretical model into software code. In the transfer from theoretical model to a computational representation analogy, intuition and expertise of others play a role, but these all have their pitfalls. When exploring new areas of research, the testing (i.e. verification and validation) is of crucial importance, as it analyses the strengths and weaknesses of the model and thus the credibility of the model outcome (chapter 4 and 5).

Two experiments are performed with CROSS in order to gain more understanding of crowd behaviour patterns. Specifically, these experiments are focussed on the relationship between a factor and behaviour clustering, i.e. a pattern in which individuals in each others vicinity display the same behaviour. The first one explores the effect of a physical factor (here: density) on behaviour clustering. The second experiment explores the effect of a social factor (here: leadership) on behaviour clustering. When interpreting the experimental results, it is important to bear in mind that the exploration of density and leadership refers to the CROSS model and not to the real world. The density experiment revealed that density is an important factor to be taken into account when seeking to understand crowd behaviour patterns. As density has a strong impact on *what* an agent (i.e. computational individual) perceives and on an agent's behavioural options. The leadership experiment shows the important effect of the social context on behaviour-specific choices, i.e. *how* behaviour is affected. What behaviour is relevant or suitable appears to be a function of the social environment *and* the internal state of an agent. The experiments further show the difference between factors from the physical and social context on the emergence of behaviour patterns. The physical context exerts a more generic relation between factors and behaviour patterns by affecting the behaviour selection process in terms of the time available for comparing behaviour options and choosing one of these. The social context describes a more specific relation between factors and behaviour patterns because it affects behaviour-specific aspects, which changes the type of patterns that emerges, but not the pattern size itself. Even though density and leadership are represented in a rather basic form, the experiments carried out with CROSS already illustrate the distinctive contribution of CROSS compared to conventional models: the level of detail provided and the multi-level description (chapter 6 and 7).

The research question is answered by combining insights from the literature, the theoretical and computational CROSS model and the results of the experiments. Firstly, *the mechanisms that underlie crowd behaviour are the same mechanisms that give rise to behaviour in general*. It makes clear that crowd behaviour should not be regarded as a special kind of behaviour that needs its own set of dedicated theories. Potentially, the entire body of knowledge on human behaviour is relevant for understanding crowd behaviour. Secondly, *explaining the mechanisms underlying crowd behaviour patterns always requires a complete image of the interplay between individuals and context*. This does not imply completeness in the sense that all relevant factors need to be incorporated. It means that the interplay between the factors one chooses to describe always need to be addressed in relation to both context and individuals. One cannot meaningfully study individuals isolated from their physical and social context. Only regarding the context without considering the individual perspective is meaningless as well. To reveal the mechanisms, the interplay between individuals and their environment always needs to be taken into account. Thirdly, some generic mechanisms may be derived

- The physical context predominantly affects *what* influences behaviour and thus affects the size or number of crowd behaviour patterns.
- The social context predominantly affects *how* behaviour is influenced and thus what type of behaviour is shown in crowd behaviour patterns.
- The internal state determines *which* behaviour is chosen.

Overall, this thesis shows the importance of the interplay between the physical and social context for behaviour. Due to the mono-disciplinary orientation of most previous crowd research, the interplay between multiple factors has traditionally been neglected. Obviously, the inclusion of context should be based on relevance rather than on field-specific preferences. Due to the multitude of potential factors, simplicity is needed to understand the dynamics of the model. It was not the aim of the research to make a "complete" model that incorporates all potentially relevant influence factors. In fact, this would make the model less transparent and make it more difficult to identify the relevant mechanisms. The model is developed in such a way that theories and ideas can easily be integrated into it and factors may easily be changed, replaced or added in future. For this study, a basic formalisation was provided that included one physical and one social factor. The plug-and-play character of this structure is suitable for exploring general mechanisms by allowing for all types of factors to be included. To develop CROSS, theories and concepts were used and adapted from a multitude of research areas. In turn, CROSS may contribute to these research areas exactly because of this integrative approach. CROSS lets researchers and practitioners look at crowds from a different perspective and by doing so it helps to shed a new light on the traditional way of using theory and methods in relation for studying crowds. CROSS contributes to crowd research, to the cognitive sciences, to the social sciences in general and to computer sciences. In addition, although the work in this thesis represents a theoretical study on crowd behaviour with an exploration in a simulated world, CROSS also potentially has practical implications for crowd management. The results and conclusions of this thesis open the way for several exciting possibilities for future directions of both research and practice (chapter 8).

Samenvatting

Dit proefschrift richt zich op het beantwoorden van de centrale onderzoeksvraag:

Welke mechanismen liggen ten grondslag aan gedragspatronen in menigten?

Als eerste stap om een verklaring te vinden voor de mechanismen die ten grondslag liggen aan gedragspatronen, is de literatuur bestudeerd (hoofdstuk 2). Er is veel literatuur waarin het gedrag van menigten vanuit een praktisch perspectief worden beschreven. Het handelen van praktijkmensen is vooral ervaring gedreven en zij handelen zelden op basis van recent onderzoek naar menige gedrag. Anderzijds, voorziet huidig menigte onderzoek niet in de (systematische) kennis die praktijkmensen nu nodig hebben. Modern menigte onderzoek voorziet in empirisch gebaseerde beschrijvingen van gedrag in menigten. Deze studies identificeren een aantal invloed factoren die als relevant gezien worden voor menigte gedrag (e.g. dichtheid, machtsstructuur). Echter, verklaringen die beschrijven *waarom* en *hoe* deze factoren hun verwachte effect hebben zijn zeldzaam. De verklaringen die gegeven worden zijn alleen toepasbaar in specifieke typen van situaties, de nadruk ligt vooral op het verklaren van verstoringen van de openbare orde en calamiteiten. Waar openbare orde onderzoek vooral verklaringen zoekt in de sociale context, zoekt calamiteitenonderzoek vooral verklaringen in de fysieke context. Toch kunnen er drie algemene inzichten geformuleerd worden vanuit modern menigte onderzoek:

- Menigte gedrag wordt gegenereerd door individuen, dat wil zeggen dat agency plaatsvindt op individu niveau (en niet op groepsniveau).
- Menigte gedrag is context afhankelijk (waarbij context zowel de fysieke als de sociale omgeving omvat).
- Menigte gedrag is dynamisch: er bestaat een continue interactie tussen individuen en omgeving in de tijd.

Gegeven deze inzichten is het opvallend dat de bestaande verklaringen geen rekening houden met de manier waarop individuen informatie verwerken en gedrag kiezen. Als gevolg daarvan zijn er nauwelijks verwijzingen naar theorieën uit de cognitieve wetenschappen in menigte onderzoek te vinden.

Op grond van de huidige staat van kennis en het feit dat het niet mogelijk is gecontroleerde experimenten met menigtes uit te voeren, zijn er twee onderzoeksbehoeften gedefinieerd: Allereerst, de behoefte aan een theoretisch model dat recht doet aan de dynamische wisselwerking tussen individuen en hun omgeving en ten tweede, de behoefte aan een methode die het mogelijk maakt om deze theorie te toetsen. De ontwikkeling van het menigte model CROSS belichaamt deze twee onderzoeksbehoeften. CROSS representeert een theorie van menigte gedrag en onderzoekt deze theorie vervolgens in simulatie experimenten.

CROSS is ontwikkeld met een geïntegreerde, multi-level en gesitueerde benadering. Het model is geïntegreerd: relevante kennis vanuit de sociale en cognitie wetenschappen is samen gevoegd in een raamwerk. Het model heeft meerdere niveaus: het groep niveau waarop gedragspatronen zichtbaar worden, het individu niveau waarop gedrag gegenereerd wordt en het cognitieve niveau waar gedrag beïnvloed wordt. Het model is gesitueerd omdat individuen *embodied* (het fysieke aspect van het hebben van een lichaam) en *embedded* (de mentale staat gerelateerd aan de huidige context en ervaring) zijn. CROSS is daarmee gebaseerd op de drie hoofdinzichten van het moderne menigte onderzoek en zet een stap verder door gedrag op het cognitieve niveau te beschrijven. Het cognitieve niveau geeft de visie van individuen als menselijke informatie verwerkende systeem weer (cognitieve systemen) (hoofdstuk 3). Deze geïntegreerde, multi-level en gesitueerde benadering van CROSS leidt tot gedetailleerde verklaringen. Het dwingt ook explicitering af zodra theorieën en ideeën in het model opgenomen worden en dat maakt ze concreter en preciezer. Het model vereist een specificatie van menigte gedrag inclusief de wijze waarop het gedrag van een individu is beïnvloed en gegenereerd wordt; een specificatie van wat het betekent om een lichaam te hebben en embedded te zijn; wat het betekent om geplaatst te zijn in een fysieke en sociale context; en tenslotte, een specificatie van hoe dit alles over de tijd verloopt. Overigens, het model maakt het mogelijk een willekeurig aantal additionele factoren, ideeën en theorieën die als relevant beschouwd worden toe te voegen. Op deze manier faciliteert het model een multi-disciplinair en integratieve aanpak.

Om het model te testen en het ontstaan van gedragspatronen te bestuderen is gekozen voor simulatie als methode. Simulatie voorziet in experimentele vrijheid alsmede de striktheid van een wetenschappelijke structuur, precies wat menigte onderzoek nodig heeft. Bestaande modellen konden niet worden gebruikt omdat zij of te eenvoudig waren om generiek menigte gedrag te kunnen weergeven, of een focus hadden dat specifiek op een bepaald type gedrag gericht was, of ze hielden geen rekening met de moderne fundamenten van menigte onderzoek. Multi-agent systemen is gekozen als aanpak om CROSS computationeel te representeren. Multi-agent systemen maakt het mogelijk de benodigde elementen mee te nemen om menigte gedrag te simuleren: de meerdere niveaus, de rijkheid van het individu niveau, de rol van context en het dynamische aspect. Om in staat te zijn om experimenten uit te voeren, is het theoretische model geformaliseerd in een computationeel model. Voor deze stap moet elk concept en elke relatie gedefinieerd worden in voor een computer interpreteerbare variabele of methode. Formalisatie is een belangrijke stap die het gebruik van bestaande kennis of data en een creatieve aanpak vergen om de overgang van idee naar code te verwezenlijken. In die overgang spelen analogie, intuïtie en de expertise van anderen een rol, maar deze hebben ieder hun valkuilen. Om in staat te zijn om nieuwe gebieden te verkennen zijn testen (verificatie en validatie) van cruciaal belang, omdat zij aangeven wat de sterke en zwakke punten van een model zijn en dus hoe geloofwaardig de uitkomsten zijn (hoofdstuk 4 en 5).

Twee experimenten zijn uitgevoerd met CROSS om meer begrip te krijgen van gedrags patronen in menigten. Specifiek zijn deze experimenten gericht op de relatie tussen een factor en gedragsclustering, i.e. een patroon waarbij mensen in elkaars nabijheid hetzelfde gedrag vertonen. Het eerste experiment verkent het effect van een fysieke factor (hier: dichtheid) op gedragsclustering en het tweede experiment verkende het effect van een sociale factor (hier: leiderschap) op gedragsclustering. Bij het interpreteren van de resultaten is het belangrijk om te realiseren dat de verkenning van dichtheid en leiderschap betrekking hebben op het menigte model CROSS en niet op de echte wereld. Het dichtheidsexperiment wijst uit dat dichtheid meegenomen dient te worden bij het begrijpen van gedragspatronen in menigten. Dichtheid heeft namelijk een sterke uitwerking op *wat* een agent (computationeel individu) waarneemt en op de gedragsopties van een agent. Het leiderschapsexperiment laat zien dat de rol van de sociale context belangrijk is voor gedrag specifieke keuzes, dat wil zeggen *hoe* gedrag beïnvloed wordt. Welke gedraging relevant of geschikt is blijkt een functie van de sociale omgeving en de interne staat van een agent te zijn. De experimenten laten bovendien het onderscheid zien tussen factoren uit in fysieke en social context in hun rol op het optreden van gedragspatronen. De fysieke context beschrijft een meer generieke relatie tussen factoren en gedragspatronen door het gedrag selectie proces te beïnvloeden in termen van de hoeveelheid tijd die beschikbaar is om gedrag te vergelijken en kiezen. De sociale context beschrijft een meer specifieke relatie tussen factoren en gedragspatronen doordat het het type gedrag beïnvloed. Deze veranderen het *type* gedragspatroon dat ontstaat in een menigte, niet de omvang van het patroon zelf. Ook al word dichtheid en leiderschap gerepresenteerd in een basale vorm, de experimenten illustreren hoe CROSS zich onderscheidt van traditionele modellen dankzij de mate van detaillering en multi-level beschrijving van het model (hoofdstuk 6 en 7).

De centrale onderzoeksvraag is beantwoord door de combinatie van inzichten uit de literatuur, het theoretische en computationele CROSS model en de resultaten van de experimenten. Op de eerste plaats, *mechanismen die ten grondslag liggen aan menigte gedrag zijn hetzelfde als de mechanismen van gedrag in het algemeen*. Het maakt duidelijk dat menigte gedrag niet gezien moet worden als een speciaal soort gedrag dat zijn eigen set van theorieën nodig heeft. Alle kennis over menselijk gedrag is potentieel relevant. Op de tweede plaats, *het verklaren van de mechanismen die ten grondslag liggen aan gedragspatronen in een menigte vereist altijd een compleet beeld van de wisselwerking tussen individuen en context*. Dit betekent niet compleetheid in de zin van het meenemen van alle relevante factoren. Het betekent wel dat er altijd aandacht besteed moet worden aan de wisselwerking tussen de factoren in de relatie tussen context en individu. Het is niet mogelijk betekenisvol individuen te bestuderen los van hun context. Enkel de context in beschouwing nemen zonder het individu perspectief mee te nemen is net zo betekenisloos. Op de derde plaats kunnen er een aantal generieke mechanismen afgeleid worden:

- De fysieke context beïnvloedt vooral *wat* de factoren zijn die gedrag beïnvloeden en daarmee dus de omvang van en aantal gedragspatronen in een menigte.
- De sociale context beïnvloedt vooral *hoe* gedrag beïnvloed wordt en daarmee welk type gedrag vertoond wordt in een in gedragspatroon in een menigte.
- De interne toestand bepaald *welk* gedrag gekozen wordt.

Over het geheel genomen laat dit proefschrift zien hoe belangrijk de wisselwerking tussen de fysieke en sociale context is voor gedrag. Doordat de meeste onderzoeken monodisciplinair georiënteerd zijn, wordt de wisselwerking tussen meerdere factoren traditioneel niet meegenomen. Het meenemen van context zou gebaseerd moeten zijn op relevantie in plaats van op veld-specifieke voorkeuren. Door de veelheid van potentiële factoren is eenvoud nodig om de dynamiek van het model te begrijpen. Het is niet het doel van dit onderzoek om een "compleet model" te maken dat alle potentieel relevante invloed factoren meeneemt. Dat zou het model minder transparant maken en het moeilijker maken om de mechanismen te vinden. Het model is zo ontwikkeld dat theorieën en ideeën gemakkelijk geïntegreerd kunnen worden en dat factoren gemakkelijk veranderd, vervangen en toegevoegd kunnen worden. Voor dit onderzoek is gebruik gemaakt van een basale formalisatie met één fysieke en één sociale factor. Het plug-and-play karakter van de structuur van het CROSS model is geschikt voor het verkennen van generieke mechanismen doordat allerlei factoren meegenomen kunnen worden. In het ontwikkelen van het CROSS model zijn theorieën en ideeën aangepast en gebruikt vanuit een variëteit aan onderzoeksgebieden. Het CROSS model kan op zijn beurt bijdragen aan deze onderzoeksgebieden, juist door zijn geïntegreerde benadering. CROSS laat onderzoekers en praktijkmensen naar menigten kijken vanuit een ander perspectief. Op die manier helpt CROSS een ander licht te werpen op de traditionele manier waarop theorieën en methoden in relatie tot menigten gehanteerd worden. CROSS draagt bij aan menigte onderzoek, de cognitieve wetenschappen, de sociale wetenschappen in het algemeen en aan informatica. Bovendien, ook al vormt het werk in dit proefschrift een theoretische studie van menigte gedrag met een verkenning in een gesimuleerde wereld, CROSS heeft ook potentiële praktische implicaties voor *crowd management*. De resultaten en de conclusies van dit proefschrift openen de weg voor meerdere mogelijkheden in de richting van zowel onderzoek als praktijk (hoofdstuk 8).

A word of thanks

When I reflect over my PhD time, I enter a mood of gratefulness and happiness. These years are filled with valuable lessons that shaped me and my future path strongly. Apart from developing a passion for my work, I learned a very important thing: science (especially a Phd) is a together-thing on your own (in Dutch: een samending in je eentje). My thesis is not very different, it is result of the interplay between my environment and me. In which the level of description and analysis remains, of course, on the Nanda-level ;) - just like my CROSS agents. I want to take the opportunity here to highlight some element of my social environment that played an important role in this thesis.

Let me start with the fixed elements of my scientific social environment: my supervisors. René, Wander and Tony, you all have been enthusiastic about this project from day 1. It is a delight to have this enthusiasm as a base. René you're my prof or like the Germans say, my 'DoktorVater'. You taught me a lot about myself through our interactions and these insights are really important to me. Your ability to reason on a high abstraction level is crucial in exploring complex new domains - thank you for showing me the tools to deal with complex problems.

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