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CROSS: Modelling Crowd Behaviour with Social-Cognitive Agents

Abstract

The use of computer simulations in crowd research is a powerful tool to describe and analyse complex social systems. This paper presents CROSS, a generic framework to model crowd simulations as a social scientific tool for understanding crowd behaviour. In CROSS, individuals are represented by social-cognitive agents that are affected by their social and physical surroundings and produce cognition-based behaviour and behaviour patterns. Understanding is sought by relating intra- and inter-individual levels of behaviour generation with behaviour pattern emergence at group level. By specifying the CROSS framework for a festival context we demonstrate how CROSS meets the need for a theory that reflects the dynamic interplay between individuals and their environment as well as the need for a method that allows for testing.

Keywords:
    Crowd Behaviour, Social-Cognitive Model, Multi-Level, Agent-Based, Crowds

Introduction

1.1   From the movement of pilgrims in Mecca to the violence and looting of rioters in the streets of London, crowds display fascinating patterns. Whenever crowds are a topic of conversation or study, usually the attention goes out to the rare instances of undesired behaviour, danger and violence, like emergencies and riots. Empirical crowd research delivers an empirically based description of crowd behaviour and provides socio-psychological explanations for disorder. However, most of the components of these models are not directly testable. Simulation provides a mean to test theory and analyse complex social systems. At the same time, existing crowd simulations rarely focus on understanding what causes the patterns under study. If they do, they tend to have a narrow focus on emergency situations and pedestrian movement, but most importantly, they are often not sufficiently based on theory and do not include the underlying decision making processes, i.e. the cognitive level (Challenger 2009; Wijermans 2011). In this paper we describe CROSS, a framework to model crowds designed to combine the best of two worlds (empirical crowd research and crowd simulation) to take a step closer in understanding crowd behaviour.

1.2   The following section describes the background of crowd research and simulation indicating the needs of these two fields. The CROSS framework, that is described next, aims at meeting the crowd research needs. It describes the general structure of a model of crowd behaviour that supports modelling crowds for a specific context (a CROSS model). To demonstrate this modelling step, crowd behaviour at a festival is modelled with use of the CROSS framework. To illustrate the way understanding is gained, the details of a CROSS model are elaborated on, based on a multi-level analysis and description of crowd behaviour. The paper concludes by reflecting on CROSS and on what the next steps should and could be.

Crowd research and simulation

2.1   Crowd research is the field studying and understanding crowd phenomena, performed by social scientists. Since the 19th century scientists try to explain crowd behaviour, especially riots. Crowd research has gone through some extensive changes, from theoretical explanations of crowd behaviour separate from context, to contextualized descriptions with an empirical base (Adang 1998; McPhail 1991; Reicher 2001; Schweingruber & Wohlstein 2005). For a long time crowds and behaviour displayed in crowds were regarded as extraordinary, requiring special explanations (Allport 1924; Le Bon 1895). 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 empirical observational studies show that behaviour in crowds is neither irrational, emotional, suggestible, destructive, spontaneous, anonymous nor uniform. The same types of rules apply within crowds that govern behaviour outside crowd situations (Adang 1998; Berk 1972; Berk 1974; Couch 1968; McPhail 1991). Several insights are especially crucial for understanding 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 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.

2.2   Although current theoretical models in crowd research, based on these insights (e.g. Adang 2010; Drury & Reicher 2000; Reicher, Spears, & Postmes 1995; Stott & Reicher 1998; Waddington, Jones, & Critcher 1989), have made great contributions 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 test their theories. The specific focus of the theories does not support a more general understanding of how crowd behaviour patterns form and change. Furthermore, their focus just covers a small part of the whole spectrum of crowd behaviour, as most crowds are not

violent. Even though the role of the social context is shown to be crucial, it is not the only relevant influence factor. The physical context cannot be neglected. In addition, the role of the internal world of a behaving individual (his/her mental state) plays a crucial role that is not addressed. The way individuals are affected can differ from one person to the other, but it may also vary from one moment to another. It is the continuous interplay between external and internal factors that gives rise to behaviour of individuals in a crowd, i.e., situatedness. Although current theories acknowledge the individual level as the level of behaviour generation, the level of detail in these theories does not describe how and why individual behaviour is chosen. Regarding individuals as black boxes (Jorna 2000) limits the explanatory power to understand why certain behaviour is chosen at a particular time and a given internal setting and why or how certain behaviour patterns occur. A second limitation is methodological: the difficulty to move from description to explanation and to perform experiments with crowds to help develop testable theories. This difficulty is due to the complex nature of crowd behaviour; the multitude of interconnected factors that can play a role are hard to control for when performing experiments. Let alone the ethical considerations, real experiments can be dangerous for subjects. Consequently, it is almost impossible to experimentally test theories and thus to take the necessary steps to understand and explain crowd behaviour[1].

2.3   Crowd simulation research, on the other hand allows for dealing with the complex nature of crowd behaviour, however, it mostly does not focus on a general understanding of crowd behaviour. Crowd simulations usually involve movement of pedestrians (Bandini, Rubagotti, Vizzari, & Shimura 2011; Helbing & Molnar 1995; Helbing, Farkas, & Vicsek 2000; Moussaïd, Helbing, & Theraulaz 2011; Still 2000; Therakomen 2001), riots (Epstein 2002; Feinberg & Johnson 1988; Granovetter 1978; Jager, Popping, & van de Sande, 2001; Patten & Arboleda-Flórez 2004; Schwarz & Mosler 2005) or specific crowd behaviour patterns (Johnson & Feinberg 1977), conformity (Tarnow 1996) or crowd tipping (Silverman, Johns, Weaver, O'Brien, & Silverman 2002). The major differences between these models concern the purpose and the use of their simulations. They either aim to display a methodology or to reproduce a specific type of crowd behaviour and only a small minority aim at gaining a better understanding of crowd behaviour.

2.4   The models that focus on methodology either demonstrate or show the explanatory power of simulations or explain what level of detail is required to develop "realistic" simulations, e.g. Granovetter (1978), Epstein (2002) and Silverman (2002). The models that replicate behaviour are capable of generating realistic and valid movement patterns. The models do not necessarily require a realistic description. Nevertheless, they tend to include relevant factors based on current knowledge and/or literature on crowd behaviour. Including knowledge can be considered as a way to add realism to the simulation outcome. For instance, more realism is gained by the inclusion of social context in some models of crowd behaviour (e.g. Helbing, Buzna, Johansson & Werner 2005; Moussaïd, Helbing, & Theraulaz 2011; Musse & Thalmann 2001; Still 2000).

2.5   Models that focus on understanding are the most relevant here (e.g. Feinberg & Johnson 1988; Johnson & Feinberg 1977; Tarnow 1996). Unfortunately, it must be concluded that, from a modern point of view, these models often are not based on the current state of knowledge of crowd research (Wijermans 2011). However, some more recent models are theoretically and empirically well-grounded. These models typically distinguish themselves by providing a description of the internal (mental) world of an individual. For instance, Jager et al. (2001) provide a simple description of clustering and approach-avoidance, yet specifically focus 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 by focusing on understanding the role of urban space in crowd movement. Schwarz (2005) describes escalation processes between civilians and the military, providing a more refined description of internal processes of individuals. However, these models have a too narrow focus on a specific behavioural outcome to help gain a more general understanding of crowd behaviour.

2.6   Overall, computational crowd models are either too simplistic to represent general crowd behaviour, because they focus too specifically on a certain type of behaviour, or they do not incorporate the modern foundation of crowd research. We developed the CROSS framework to overcome these limitations and use simulation as a social scientific tool to help increase understanding of crowd behaviour.

🌍 CROSS

3.1   CROSS represents a framework to model CROwd behaviour in a Simulation with Situated individuals. The *CROSS framework* represents a generic structure that can be used to design and explore any model of crowd behaviour. *CROSS models* on the other hand specify this generic structure for particular crowd contexts. Models developed with the CROSS framework allow for exploring 'why' and 'how' crowd behaviour patterns emerge by including a *multi-level analysis*.

3.2   From the current insights and limitations in crowd research we derived three requirements (R) for crowd modelling:

- R1. A crowd model should represent the main insights gained by current crowd research: the individual-level of agency, the role of the social and physical environment or context and the dynamic nature of crowd behaviour.
- R2. A description of behaviour on the cognitive level is needed. To explain (group level) crowd behaviour a description of individual behaviour in a crowd should involve the internal state and processes of an individual (cognitive level).
- R3. A focus on crowd behaviour in a general sense is needed, rather than an exclusive focus on deviant crowd behaviour, such as riots and stampedes.

Consequently, CROSS allows for studying crowd behaviour on multiple levels: the group level where behaviour patterns emerge; the individual level where behaviour is generated and the local influences of the physical and social environment originate from; and the cognitive level where the individual is affected and behaviour is chosen.

3.3   The following sections will describe the CROSS framework; an application for a festival context[2], i.e. a CROSS model; and the use of CROSS in performing a multi-level analysis.

The CROSS framework

3.4   The CROSS framework represents a generic structure for a crowd simulation that supports and guides crowd model development. CROSS embodies the above state requirements by representing a context dependent, multi-agent framework. More precisely, it represents multiple agents that interact with their physical and social environment in an agent-based model (R1 & R2). All influences go via the individual, which implies that in describing group level patterns, explanations should be sought by relating the group level to the individual and cognitive level (R2).

The environment

3.5   The environment in the crowd model represents the world the agents live in, including both the physical and social space. The physical environment

represents the physical location where the agents are gathered, with all relevant points included (Point of Interest, POI e.g. a specific building), see figure 1. The agents are situated in the social environment. Here one can define the size of the crowd and other group level characteristics of a crowd.
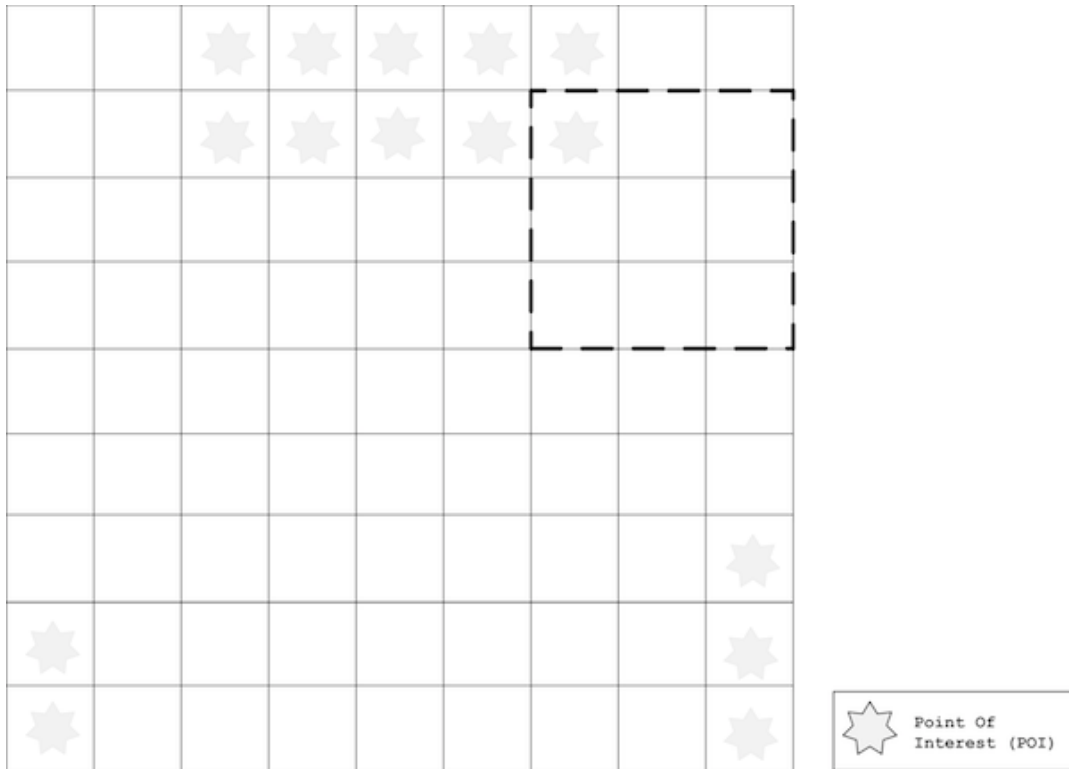

Figure 1. The environment of CROSS. Represents the space where agents can be placed as well as where the points of interest (POIs) are.

The agents

3.6   Agents in the CROSS framework interact in their environment and produce behaviour as a result of the interplay between their internal and external world. CROSS agents are considered to be situated (Wilson & Keil 1999), which means that they are both embodied and embedded. Embodiment refers to the physical, bodily characteristics that influence human information processing. For instance, only what is perceived influences behaviour, thus something that happens behind a person that he does not perceive will not affect his behaviour. To be embedded relates to performing situation-dependent behaviour based on current external and internal settings. For example, applauding at the end of a performance requires knowledge of a norm (i.e., action) coupled to a certain situation.

3.7   CROSS agents are described on the cognitive level (R2). That allows for tracing what behaviour is chosen and why, given the internal state of that agent at any given moment in time. The cognitive level describes the way the agent processes knowledge in order to decide or act on behaviour, an agent is a cognitive system. A cognitive system defines the structure where relevant bodily elements are incorporated, where knowledge can be changed and used and processes of perception and behaviour selection allow for the interaction of an agent with its environment via perceiving and acting. In CROSS, the cognitive level of an agent distinguishes between physiology, memory (knowledge representation) and processes (perception and behaviour selection), see figure 2.
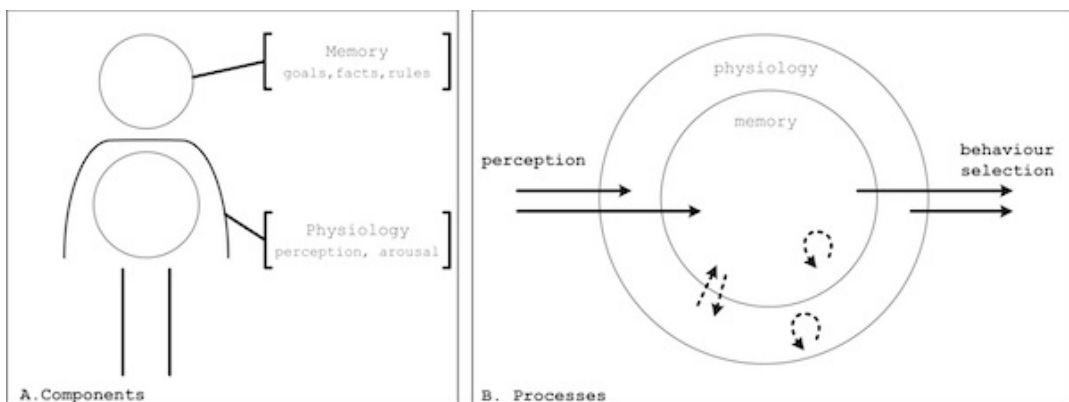
Figure 2. The cognitive level of agents in the CROSS framework: components (A) and processes (B). A CROSS agent consists of a physiology (body) and a memory (knowledge representation) component and two main processes (perception and behaviour selection) to interact with the world. Note, the dotted arrows form a part of the internal perception (update) processes.

Physiology

3.8   Physiology or architecture represents the structure of cognition (Newell 1990). It is where individual knowledge can be found and mental processes take place. In addition, it also involves the physical properties of the natural system (being embodied, having behavioural and cognitive constraints).

3.9   For CROSS agents this involves the inclusion of the most essential physiological factors influencing crowd behaviour: arousal and limitations in perception. Perceptual limitations imply that whatever sensor one chooses to model one needs to specify the perceptual range. This limitation is a direct consequence of being embodied (Ballard & Sprague 2007). Arousal corresponds to behaviour that is related to short-term survival mechanisms (e.g., fight/flight, Baron & Richardson 1994). It allows human beings to react to a potentially life-threatening situation. Furthermore, arousal has been related to types of cognitive processing (e.g., reasoned vs. automated processing, narrowed vs. wide attention focus). People lack among others the time, information or incentive to employ an optimising strategy (Simon 1976, Schiffrin 1975 in Jager 2000). Both the constraints on perception and cognitive processing are formalisations of bounded rationality (Simon 1957).

Memory

3.10   Memory represents an individual's knowledge and processes that allow an individual to interact with its environment. In CROSS, the concept of memory is based on Anderson's theory (Anderson 2007) which lies at the base of the cognitive architecture ACT-R (Anderson & Lebiere 1998). This theory describes how memory works in functional level terms. The description includes how memory elements become more dominant (i.e., more highly activated) and change in content (i.e., learning). In addition to this, the memory theory also explains how behaviour is affected, for instance how typical human errors arise in performing or learning tasks, for instance, in short term memory tests, or in language learning.

3.11   Memory of CROSS agents consists of memory elements. Each element has two important properties: 1) it has content, and 2) it has an activation level. Content refers to knowledge and how knowledge is used. The activation level reflects how likely it is that this memory element affects behaviour. Both content and activation of a memory element change over time. A change in content represents learning, forgetting or reorganising. A change in dominance represents what is influencing behaviour at a given moment in time, i.e., the internal (mental) state. All knowledge, i.e., the content of an agent's memory elements, is represented either in 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.[3]

3.12   So far we adopted the memory structure of Andersons' theory closely, however in specifying each memory type for CROSS agents we will deviate from Anderson's memory theory. Moving from the cognitive to the social domain causes this deviation. Our focus lies on understanding crowd behaviour rather than describing and reproducing higher cognition, such as learning and planning tasks.

The memory elements

3.13   A goal represents the state desired by an individual, making a particular behaviour more or less relevant to choose[4] (goal is used in the motivational sense here as opposed to the intentional use of the concept)[5]. Four goals are considered relevant in a crowd context: subsistence, safety, social and personal goals[6]. They represent the desire of an agent to respectively a) preserve energy, b) remain safe, c) belong to a group, and lastly, d) enjoy the festival individually. The more dominant a goal is, the more probable it is that behaviour is chosen that satisfies that goal. For example, if the safety goal is most dominant, because the agent is in a very crowded place, then behaviour 'walking away from high density areas' will become more likely to be chosen. Goal dominance is the result of the preferred level of satisfaction and the actual satisfaction of that goal, see equation 1.

$$\text{Goal dominance} = \text{goal\_satisfaction} - \text{goal\_preference} \qquad (1)$$

3.14   Facts, however, represent a piece of factual or declarative knowledge[7]. This kind of knowledge assists an agent in interpreting what it sees. Furthermore, facts also allow distinguishing between behavioural options, depending on whether these options are preferable or more relevant given a particular situation. The CROSS agent knows three types of facts: area facts, personal facts, and behaviour facts. All facts allow the agent to recognise points of interests, other people, or the behaviour that others perform. Behaviour facts serve another purpose, they support in making a suitable choice in behaviour. Behaviour facts convey expectation values that indicate how satisfying it would be to perform a particular behaviour.

3.15   The activation for this type of knowledge is related to the time it takes to retrieve a fact from memory. Facts with a high activation level are easily retrievable, but if it takes too much time to retrieve a fact an agent is not able to use it, i.e., forgets it. The activation (A) of a behavoural rule (i) is represented by equation 2 and 3. These equations represent a neuron activation equation that increases the activation of the memory elements that are primed and thus becomes more probable or relevant for the agent at that moment (Anderson 2007).

$$A_i = B_i + \sum_{j \in C} W_j S_{ji} \qquad (2)$$

$$B \approx \ln \left[\sum_{i=1}^{k} \frac{1}{\sqrt{t_i}} + \frac{2(n-k)}{\sqrt{t_n + \sqrt{t_k}}} \right] \qquad (3)$$

3.16   Rules refer to the internal representation of an action, which is called procedural knowledge. In CROSS, behaviour rules mainly concern motor action[8]. A behaviour rule allows an agent to exhibit specific behaviour in as far as this behaviour is known. The activation value gives rise to a (dynamic) hierarchy in behaviour an agent knows. The higher the activation level, the more likely it is that this behaviour will be chosen. The changes in activation over time result in a dynamic ordering of behaviour. The activation value of a rule is also described in an activation-term equation (see equation 2 and 3). 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 before execution.

Processes

3.17 The dynamic element of the CROSS framework is represented by the continuous interaction of an agent with its environment via two processes: perception and behaviour selection.

Perception

3.18 Perception[9] describes the changes in the agent's internal state as a result of interacting with the external and its internal world. In the CROSS framework, the way perception affects the internal state of an agent distinguishes three types of perceptual influences: priming, physiology update and memory update of cognitive elements.

3.19 Perception starts with retrieving information from the world that is visible to an agent (taking limitations on perception into account). Depending on what is perceived, the corresponding internal representation is made more active via priming. Those behaviour rules that are perceived in the environment increase, whereas the activity of non-perceived behaviour rules decrease. After priming, the specific content is updated both physiologically (physiology update) and within memory (memory update of goals and facts).

3.20 The physiological update represents the changes of levels of the physiological elements due to both external and internal perception. It concerns an update of arousal and any other included context-depending physiological element. The way the levels are updated depends on the context- or theory-related choice within a CROSS model, i.e. they are not part of the generic framework.

3.21 The memory update on the other hand represents the change in the content of memory elements due to both external and internal perception. It concerns an update of the goals, i.e., in terms of the degree of satisfaction, and the behaviour facts, i.e., in terms of the expectations, making a certain type of behaviour more or less suitable in a particular context. Each goal has its own satisfaction-function that is based on context-related knowledge and assumptions.

Behaviour selection

3.22 Behaviour selection is the other main process in the CROSS framework. Behaviour selection involves a process of selecting 'suitable' behaviour within a certain amount of time, visualised in figure 3. Suitable behaviour is behaviour that best satisfies the goal that is most dominant at a particular moment. In the behaviour selection process, time and comparison are the two main parameters.

3.23 The time an agent has to choose behaviour is implemented as a direct link between the arousal level and the internal time to compare different outcomes of behaviour with each other and then to make a choice. In line with the amount of time an agent has available, the selection process starts by retrieving behaviour with the highest activation level. For as long as there is time left, this behaviour is compared to behaviour that is next in line. The best behaviour option is chosen and used for further comparison. Retrieval of memory elements takes time, which is based on its activation value. Behaviour with the highest activation levels are not only compared first, they are also retrieved faster.

3.24 The comparison of behaviour occurs in a specific order. The order is based on the activation value of the behaviour rules. Since the activation level is a consequence of perception, the ordering of behaviour rules is dynamic and situated. The comparison itself is represented in a function that attributes a utility value ($bUtil_b$) to each behaviour under comparison (see equation 4).

$$bUtil_b = \sum_{g=1}^{4} goalDom_g \cdot bExpect_g \qquad (4)$$

3.25 The utility value represents the relevance of certain behaviour (b) based on the agent's internal state, i.e., goal dominance ($goalDom_g$), at that particular time. The comparison function is based on the expectation ($bExpect_g$) of behaviour in combination with goal dominance ($goalDom_g$). The expectation indicates the expected fulfilment of the corresponding goal (g) when exhibiting certain behaviour. The comparison value incorporates the contribution of all goals in accordance with their dominance.
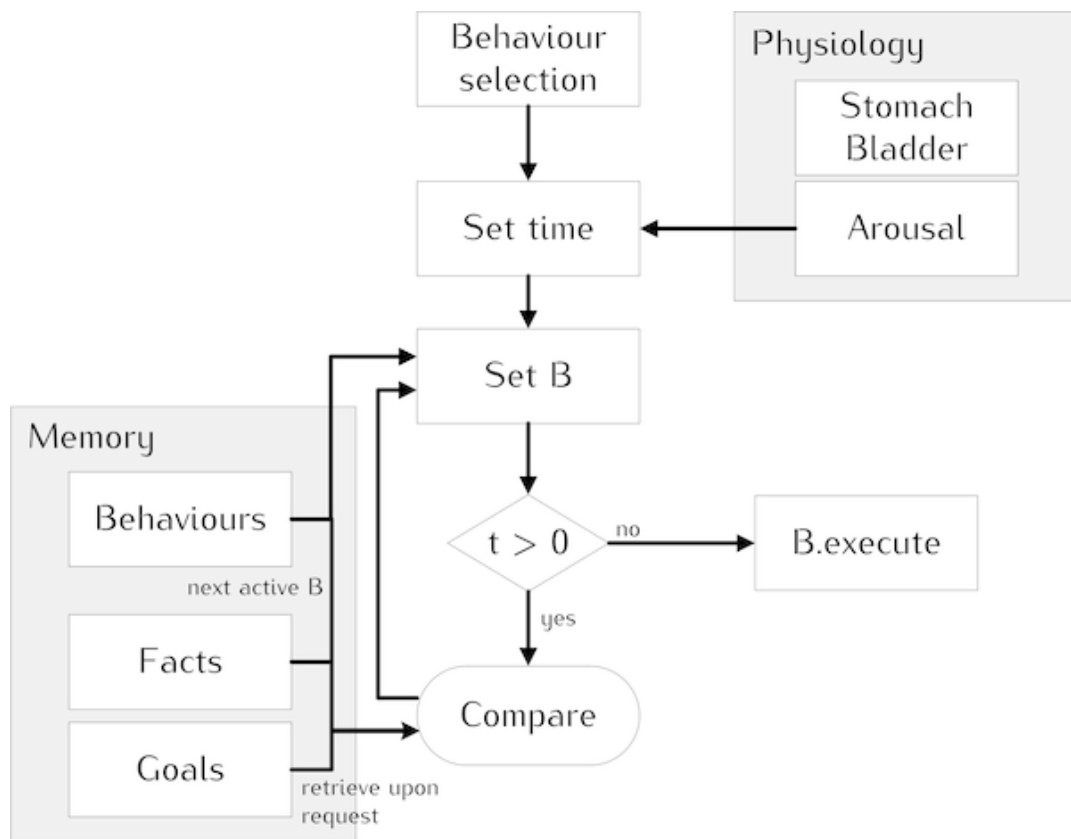
Figure 3. The behaviour selection process of a CROSS agent. An agent chooses the 'suitable' behaviour based on the expectations an agent has of a behaviour. The decision process is affected by time and the order of comparison (behaviour options are ordered based on their current activation level).

Putting it all together

3.26 The general structure for the environment, the agents and the element of time together form the CROSS framework. Figure 4 illustrates a snap-shot of the interaction between agents and their environment in CROSS. The figure also visualises the multi-level aspect of CROSS. On the macro level one sees an agent joining another agent and adopting behaviour. On the micro level one is able to follow why each agent is choosing this particular behaviour. Any chosen behaviour can be related to external and internal settings of that agent.

3.27 Let's zoom in on agent 2. On the cognitive level, its internal state consists of goal dominance in which the identity goal is most dominant, shortly followed by its social goal. Furthermore, the internal representation of behaviour an agent can show has currently the order of type [2,3,0,1]. On the individual level one can see agent 2 is executing behaviour type 2 and as a result it moved closer to the group of people in the next time step (t=1). The behaviour ranking (t=0) already indicated that behaviour type 2 had a higher probability and since it is executed it was apparently also 'suitable' given the current goal dominance setting. When looking one time step further (t=1) on the cognitive level, we can see that things have changed. Both the agent's identity and social goals have been satisfied, however now the social goal has become dominant. In addition to the changes in goal dominance, also the behaviour ranking has changed into [2,0,1,3]. Recall that behaviour ranking is a result of the behaviour that agent 2 perceived (that affects the activation level of the behaviour representation via priming). Based on the internal state (t=1) the current behaviour of agent 2 has changed into type 1.
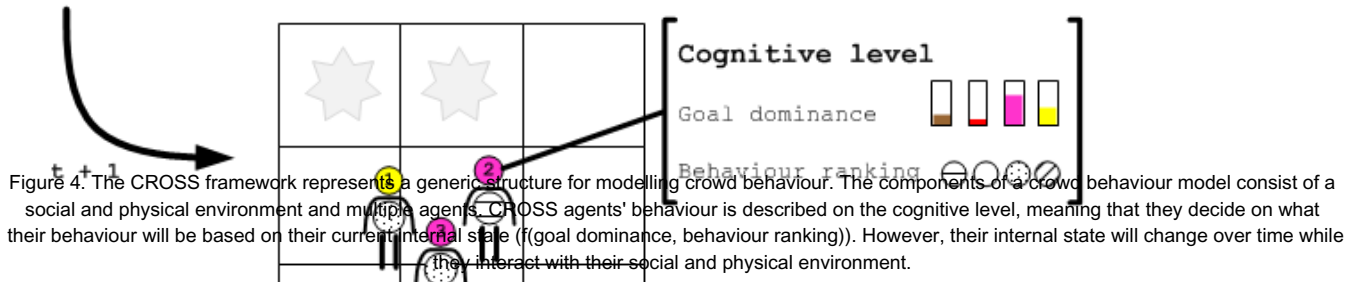
Figure 4. The CROSS framework represents a generic structure for modelling crowd behaviour. The components of a crowd behaviour model consist of a social and physical environment and multiple agents. CROSS agents' behaviour is described on the cognitive level, meaning that they decide on what their behaviour will be based on their current internal state (f(goal dominance, behaviour ranking)). However, their internal state will change over time while they interact with their social and physical environment.

3.28 When moving to the last time step visualised in figure 4, agent 2 still displays behaviour type 1, which is apparently still the most suitable given the goal and behaviour dominance. Both on the group level and on the individual level the group of three performs the same behaviour as in the last time step (t=2), however internally agent 2 has changed. Goal dominance is less prominent, and the behaviour ranking is now [1,2,0,3] which fits more closely to the behaviour that is shown. It is impossible to see, however what internal/external changes will make other behaviour more suitable for t+1.

3.29 Overall, CROSS describes crowd behaviour as behaviour that is generated on the cognitive level, while being affected by all levels (group, individual, cognitive). Explanation is sought by relating the different levels to each other.

🌐 A CROSS model: festival crowd behaviour
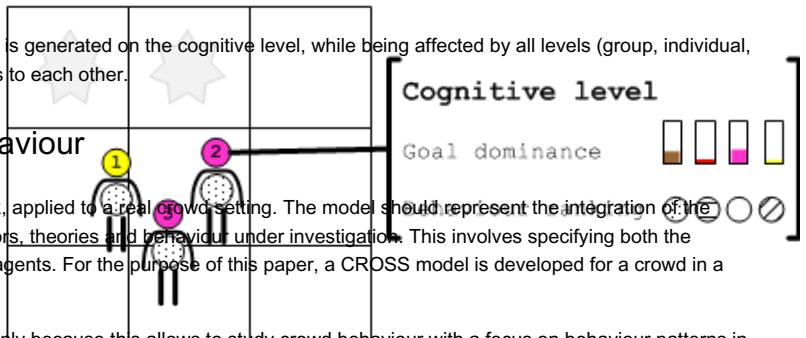
4.1 A CROSS model is the specification of the CROSS framework, applied to a real crowd setting. The model should represent the integration of the generic CROSS framework with context-specific relevant factors, theories and behaviour under investigation. This involves specifying both the physical and social environment and the internal world of the agents. For the purpose of this paper, a CROSS model is developed for a crowd in a festival context.

4.2 We chose to apply the CROSS model to a festival context mainly because this allows to study crowd behaviour with a focus on behaviour patterns in general (recall requirement R3) within a clearly defined and well-described setting (Kemp, Hill, & Upton 2004; Kemp, Hill, Upton, & Hamilton 2007). Since the CROSS agents in the model are supposed to act at a festival, the CROSS framework is specified in such a way that the agents are able to witness musical entertainment in an outdoor setting and are motivated to do so.

4.3 Movie 1 illustrates the CROSS model in a festival context. The CROSS agents' behaviour is based on the influences of their local surroundings and internal state. Based on their goals and on the dominance of these goals, a CROSS agent chooses to be close to the stage or with friends, to dance, to go to the toilet or to go to the bar. The colours indicate the agents' dominant goal: yellow: identity (listening to music); pink: social (being close to others); red: safety (avoid crowded areas); brown: subsistence (urge to visit the toilet or bar). When orange the agent is inhibited to move.

Movie 1. The CROSS model in a festival context

Below, we will explain how the CROSS framework has been specified to a model of crowd behaviour for both the environment and the agents.

The environment

4.4   Both the physical environment and the social environment are specified for a festival context. The physical environment involves a festival area and relevant festival objects, such as a bar, toilets, and a stage represented by a grid layer. The physical representations of the environment allow the agents to distinguish between walkable and non-walkable areas on the festival area as well as identifying specific objects and places that may fulfil the agents' goals, i.e., points of interests (POIs). For example, listening to music near the stage or having a drink at the bar relate physical location to goal-satisfaction.

4.5   The social environment reflects the social setting, and is a group level representation of a festival crowd. This social structure is formalised in a network topology. It represents the number of agents, but also social connections (who knows who). Although the actual influence of the social environment remains an internal activity in each agent[10], the network topology serves initialisation, experimenting and logging purposes.

Relevant physical and social environmental factors

4.6   The selection of environmental factors is based on existing knowledge. In the literature, several physical factors have been linked to crowd behaviour, some of the most discussed factors involve density (persons/m^2), noise, scent and weather conditions (Krahé 2001; van de Sande 2006); (Geen & O'Neal 1969; Rotten, Barry, Milligan & Fitzpatrick 1979). In the CROSS model, density is included 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, the causal mechanisms are not clear, because the reported correlations don't describe how behaviour is affected that explains the group level patterns. They are therefore not included.

4.7   Social factors addressed by crowd research indicate that the presence of identifiable groups (Aveni 1977; Kemp , Hill & Upton 2004; Kemp, Hill, Upton & Hamilton 2007) and social structure (e.g. initiators, leaders, hard-core members, followers and hangers-on (van de Sande 2006) is relevant. Social structure is described in terms of friendship, in-group/out-group settings and power relationships. For reasons of simplicity only friendship and leadership as a power-relationship were included.

4.8   Note that the aim of the study was not to build a complete model in the sense that all relevant factors were incorporated, but rather to incorporate the relevant mechanisms that underlie crowd behaviour patterns.

Agents

4.9   The agent's physiology and memory are specified for a festival context as well.

Physiology

4.10   In addition to the framework-defined physiological elements (limited perception and arousal), the festival agents were further equipped with a bladder and stomach since people eat, drink and go to the toilet during a festival.

Memory

4.11   To fill the CROSS agents 'minds' with relevant knowledge, each type of memory element is specified in relation to crowd behaviour at a festival.

4.12   Goals are a part of the generic structure of the CROSS framework. Context, however, specifies what and in what way goals are being satisfied or not. Facts, on the other hand are fully context-dependent. Given the festival context with the physical and social environment, facts are needed that allow the festival agent to recognise points of interests such as the stage, bar and toilet (area facts); and other people as friend or leader (person facts). Behaviour facts are specified in terms of expectation values for each behaviour: how satisfying would it be to perform a particular behaviour. The rules for the CROSS festival model concern behaviour an agent knows. For the sake of simplicity of a first implementation, the relevant festival behaviour has been restricted to walking, running, and dancing.

Processes

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

4.14   Perception that is context-dependent involves both the physiological and the memory update. The physiological update involves an increase/decrease in arousal, stomach and bladder levels. Arousal is represented by a threshold function that relates heightened density to a heightened state of alertness (arousal level). This is related to the fact that as soon as density imposes restrictions on the freedom of movement, an increasing effect on arousal occurs. The bladder and stomach levels represent 'fullness' following a linear function. The linear functions simply increase/decrease the fullness of the bladder and stomach over 1000 ticks unless emptied/filled by a toilet/bar visit.

4.15   The memory update involves the update of goal satisfaction. The subsistence goal is directly related to the physiological state, the dominant urge: either bladder or stomach. The safety goal is related to the subjective, local perception of density. 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[11]. Local density affects an agent via a sigmoid function (a smooth step-function). The relation between perceived density and satisfaction level is identical for each agent. However, the way this level is interpreted is heterogeneous (via the preference of an agent) and gives rise to the subjective role that determines the dominance of a goal. The satisfaction of the social goal is formalised as a threshold function related to the number and kind of agents in the immediate vicinity. The identity goal is related to the distance to the stage, where being closer to the stage increases satisfaction, which is represented in a threshold function as well. In addition to the goals, the memory update also involves the update of behaviour facts. When perceiving a leader behave, this particular behaviour fact is changed by temporary increasing the expectation to satisfying the social goal.

A multi-level analysis using CROSS

5.1 Models developed with the CROSS framework allow for exploring 'why' and 'how' crowd behaviour patterns emerge by performing a multi-level analysis. The CROSS framework thus also supports theory testing/experimenting.

5.2 Imagine a typical phenomenon of two persons going to the toilet together, see movie 2. CROSS enables you to explain how this pattern arises by relating this group level pattern to the level on which behavioural decision making is performed (individual, cognitive level). The CROSS structure forces to make explicit the individual and/or cognitive level variables, apart from the classical experimental design [12] in finding an explanation for a certain crowd pattern. The way of influence is traced in providing explanations by relating the group level with the inter- and intra-individual level.

Movie 2. Two agents walking towards the toilets and turning around, driven by different goals (upperleft corner)

5.3 By tracing the behaviour choices of agents, e.g., figure 5, one can see why agents are engaged in the same or similar behaviour on the individual level. As the colours in the movie already indicate, a behaviour can be chosen for different reasons since agent 1 was walking because its physiology drives the agent to empty its bladder, whereas other agent is walking because of social reasons. These reasons can be traced by tracing for instance the goal dominance and the behaviour utility of an agent, e.g., figure 6 and 7.

5.4 It is thus part of one's experimental design to define which variables are traced under the hood that are included in data analysis. These variables are so-called life histories of an agent, i.e., the selection of variables one decides to follow are the dependent variables for explaining a group level relation given an experiment.
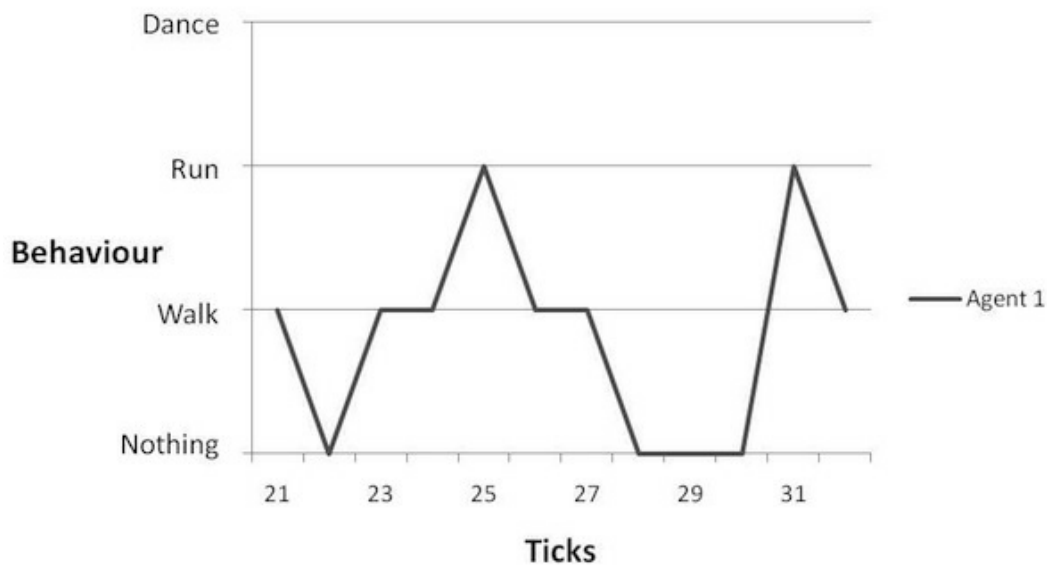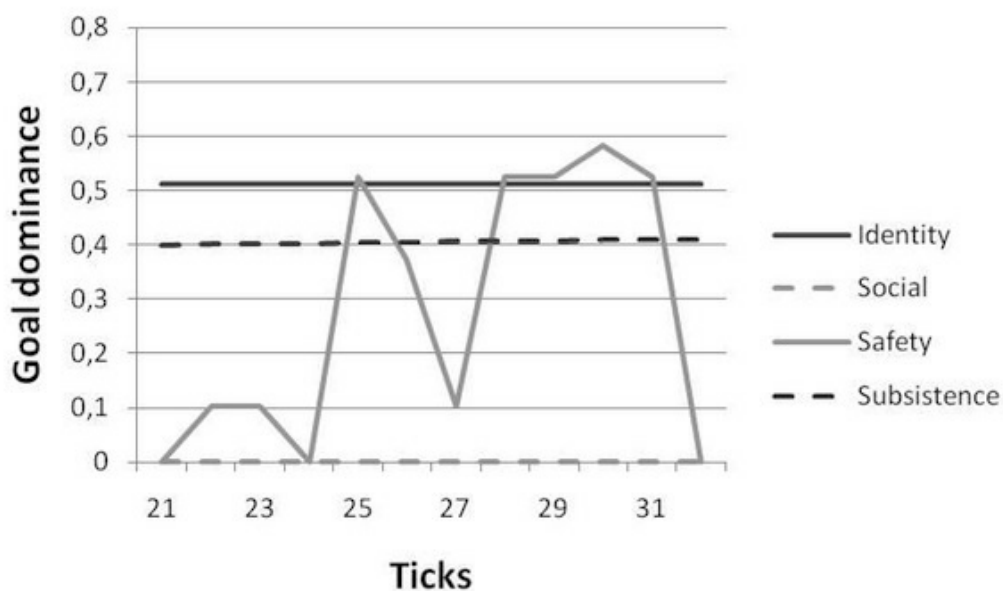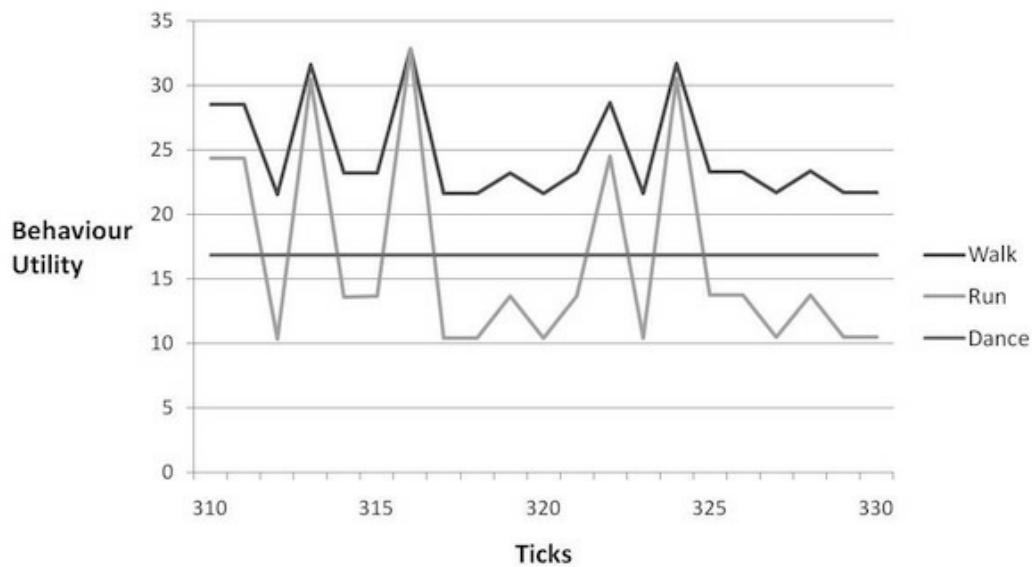
Figure 5. Behaviour choices of an agent

Figure 6. The goal dominance of an agent

Figure 7. The behaviour utility of an agent

Conclusion

6.1 The CROSS framework is a social scientific tool to gain more understanding of crowd behaviour. Understanding is sought by relating the group level to the individual level where behaviour arises. The CROSS framework represents a generic structure to design and explore any type of crowd behaviour. CROSS thereby supports simulation modelling, performing and analysis of simulation experiments. The use of this framework has been applied by modelling crowd behaviour at a festival where the multi-level analysis was demonstrated.

6.2 The future focus of CROSS will lie in the development of CROSS models for different crowd contexts as well as in the validation of the generic CROSS framework and specific CROSS models. Validation forms one of the most important future directions in crowd behaviour simulation models like CROSS. At any stage of modelling (the theoretical, the computational and the experimental stage of modelling Gilbert & Troitzsch 2005), validation is important (Balci 1998). Both the theoretical and computational model validation should be sought in the social and cognitive plausibility as well as in empirical validation. For instance, in CROSS, social representations are integrated into a cognitive structure. This forms in a sense a new 'theory' that needs to be grounded and discussed with peers. Empirical validation concerns closing the scientific empirical cycle to be able to draw real-world conclusions. This involves gathering and using empirical data as well as defining suitable behaviour measures that allow for answering research questions as well as comparing real and simulated data.

6.3 CROSS contributes to crowd research by meeting the needs in crowd research in two ways 1) supporting the development of testable theories (modelling) grounded in current insights of crowd research and 2) providing a methodology that allows for testing (simulation experiments) and performing multi-level analysis to gain more understanding. The contribution of CROSS to crowd simulation is the focus on crowd models for understanding. Understanding is embodied by CROSS by incorporating the modern foundation of crowd research, the focus on general crowd behaviour and the cognitive level of description added.

6.4 Overall, CROSS lays the foundation for a modern generation of crowd models, where the boundaries of modelling are given by the framework, not by the borders of disciplines. This provides more explanatory power to crowd research and simulation and stimulates opportunities for data gathering, validation and non-scientific purposes, such as crowd management.

In memoriam

A month before this paper appeared, our colleague René Jorna suddenly passed away. We would like to take this opportunity to honour his sharp mind and remarkable personality. René was uncompromising in his passion for good science and being true with everyone he interacted with. In five years of intense collaboration with lots of opportunities to agree and disagree, he contributed significantly in integrating cognitive science with social and computer science. René, your lively and challenging stimuli will be missed.

Nanda Wijermans, Wander Jager, Tony van Vliet and Otto Adang

Notes

[1] Some exceptions of experiments with crowds exist. The research institute TNO and the Police Academy of the Netherlands performed experiments during military and riot police training (Bruinsma-Jakobsen 2007; van Vliet 2007; Wetzer et al. 2010).

[2] This festival CROSS model is developed in Repast symphony and is publicly available on Sourceforge (CROSS 2010) and OpenABM (CROSS 2012).

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

[4] The inclusion of goals is considered necessary following Newell's principle of rationality: actions are selected to attain the individual's goals (Newell 1982).

[5] "Schoelles: 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, pp. 325)

[6] Goal choices are inspired on the 'need' concepts of Max-Neef (1993) and Maslow's motivation concepts(Maslow 1943). We explicitly include a dynamic hierarchical structure of goals and thus reject Maslow's fixed hierarchical structure (Wahba & Bridwell 1976).

[7] In terms of Anderson & Lebiere (1998): Facts, or declarative knowledge are represented in so-called chunks.

[8] Other procedure rules could concern internal processes. For instance, learning based on the content of memory.

[9] In CROSS, perception is `hard-coded', which means that no intelligent algorithm is behind perception.

[10] Recall that within CROSS, the social environment is a perception of each individual agent of other agents in its environment. The relationship an agent has with others is therefore an internal representation at the cognitive level of the agent.

[11] 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, in Adang's initiation-escalation

model (Adang 2010). This is, however, not addressed here.

[12] A classical experimental design usually involves the relation between two variables on one aggregation level. Where one variable is systematically manipulated (independent variable - a suspected influence factor) and the other is measured for effect (dependent variable - a pattern).

References

ADANG, O. (1998). *Hooligans, Autonomen, Agenten. Geweld en Politie-optreden in Relsituaties*. Alphen aan den Rijn: Samson.

ADANG, O. (2010). Initiation and escalation of collective violence: a comparative observational study of protest and football events. In T. Madensen & J. Knutsson (Eds.), *Preventing Crowd Violence* (pp. 47-68). Boulder, USA: Criminal Justice Press.

ALLPORT, F. H. (1924). *Social Psychology*. Boston: Houghton Mifflin.

ANDERSON, J. R. (2007). *How Can the Human Mind Occur in the Physical Universe*. New York: Oxford University Press. [doi:10.1093/acprof:oso/9780195324259.001.0001]

ANDERSON, J. R., & Lebière, C. (1998). *The atomic components of thought*. Mahwah, NJ: Erlbaum.

AVENI, A. (1977). The not-so-lonely Crowd: Friendship groups in collective behavior. *Sociometry*, *40*, 96-99. [doi:10.2307/3033551]

BALCI, O. (1998). Verification, Validation, and Testing. In J. Banks (Ed.), *The Handbook of Simulation* (pp. 335-396). New York: John Wiley & Sons. [doi:10.1002/9780470172445.ch10]

BALLARD, D., & Sprague, N. (2007). Integrated Models of Cognitive Systems. In W. D. Gray (Ed.), (pp. 283-296). New York: Oxford University Press.

BANDINI, S., Rubagotti, F., Vizzari, G., & Shimura, K. (2011). An agent model of pedestrian and group dynamics: experiments on group cohesion. *AI* IA 2011: Artificial Intelligence Around Man and Beyond*, 6934, 104-116.

BARON, R. A., & Richardson, D. R. (1994). *Human Aggression*. New York: Plenum Press.

BERK, R. (1972). The emergence of muted violence in crowd behavior: A case study of an almost race riot. In J. F. Short & M. Wolfgang (Eds.), *Collective Violence* (pp. 309-328). Chicago: Aldine.

BERK, R. (1974). *Collective Behavior*. (C. Brown, Ed.). Dubuque, IA: Wm.

BRUINSMA-JAKOBSEN, S. (2007). *Interaction between Crowd and Police: Effects of Anonymity, Expectations, and Arousal on Police use of Force*. Master thesis. University of Leiden.

CHALLENGER, R., Clegg, C. W., & Robinson, M. A. (2009). Understanding Crowd Behaviours. In M. Leigh (Ed.), *Simulation Tools*. London: Cabinet Office.

COUCH, C. J. (1968). Collective Behavior: An Examination of Some Stereotypes. *Social Problems*, *15*(3), 310-322. [doi:10.2307/799787]

CROSS (2010). CROSS festival crowd model. Sourceforge. http://sourceforge.net/projects/crossmodel/

CROSS (2012). CROSS festival crowd model. OpenABM. http://www.openabm.org/model/2310/version/2/view

DRURY, J., & Reicher, S. (2000). Collective action and psychological change: The emergence of new social identities. *British Journal of Social Psychology*, *39*, 579-604. [doi:10.1348/014466600164642]

EPSTEIN, J. (2002). Modeling civil violence: An agent-based computational approach. In *Proceedings of the National Academy of Sciences* (Vol. 99, pp. 7243-7250). [doi:10.1073/pnas.092080199]

FEINBERG, W. E., & Johnson, N. R. (1988). "Outside agitators" and crowds: Results from a computer simulation model. *Social Forces*, *67*(2), 398-423. [doi:10.1093/sf/67.2.398]

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. [doi:10.1037/h0026885]

GILBERT, N., & Troitzsch, K. G. (2005). *Simulation for the social scientist* (2nd ed.). Open university Press.

GRANOVETTER, M. (1978). Threshold Models of Collective Behavior. *The American Journal of Sociology*, *83*(6), 1420-1443. [doi:10.1086/226707]

GRAY, W. D. (Ed.) (2007). *Integrated Models of Cognitive Systems*. New York: Oxford University Press. [doi:10.1093/acprof:oso/9780195189193.001.0001]

HELBING, D., & Molnar, P. (1995). Social force model for pedestrian dynamics. *Physical Review*, *51*(5), 4282-4286. [doi:10.1103/physreve.51.4282]

HELBING, D., Farkas, I., & Vicsek, T. (2000). Simulating dynamical features of escape panic. *Nature*, *407*(6803), 487-490. doi:10.1038/35035023 [doi:10.1038/35035023]

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. [doi:10.1287/trsc.1040.0108]

JAGER, W. (2000, June). *Modelling Consumer Behaviour*. PhD 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). http://jasss.soc.surrey.ac.uk/4/3/7.html

JOHNSON, N. R., & Feinberg, W. E. (1977). A computer simulation of the emergence of consensus in crowds. *American Sociological Review*, *42*(3), 505-521. [doi:10.2307/2094754]

JORNA, R. J. (2000). *De "zwarte doos" in de bedrijfskunde: Cognitie in actie*. University of Groningen.

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

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

KRAHÉ, B. (2001). *The social psychology of aggression*. In M. Hewstone, (Ed.). Sussex: Psychology Press.

LE BON, G. (1895). *La Psychologie des Foules*. Paris: Alcan.

MASLOW, A. H. (1943). A theory of human motivation. *Psychological Review*, *50*, 370-396. [doi:10.1037/h0054346]

MAX-NEEF, M. (1993). Development and human needs. In P. Ekins & M. Max-Neef (Eds.), *Real-life economics: Understanding wealth creation* (p. 197). London: Routledge.

MCPHAIL, C. (1991). *The Myth of the Madding Crowd*. In J. D. Wright(Ed.). New York: Aldine de Gruyter.

MOUSSAD, M., Helbing, D., & Theraulaz, G. (2011). How simple rules determine pedestrian behavior and crowd disasters. *Proceedings of the National Academy of Sciences*, *108*(17), 6884-6888. [doi:10.1073/pnas.1016507108]

MUSSE, S. R., & 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. [doi:10.1109/2945.928167]

NEWELL, A. (1982). The knowledge level. *Artificial Intelligence*, *18*(1), 87-127. [doi:10.1016/0004-3702(82)90012-1]

NEWELL, A. (1990). *Unified theories of cognition* (3rd Edition). Cambridge: Harvard University Press.

PATTEN, S. B., & Arboleda-Flórez, J. A. (2004). Epidemic theory and group violence. *Social Psychiatry and Psychiatric Epidemiology*, *39*(11), 853-856. [doi:10.1007/s00127-004-0867-9]

REICHER, S. D., Spears, R., & Postmes, T. (1995). A social identity model of deindividuation phenomena. *European Review of Social Psychology*, 6, 161-198. [doi:10.1080/14792779443000049]

REICHER, S. (2001). The Psychology of Crowd Dynamics. In M. A. Hogg & R. S. Tindale (Eds.), *Blackwell Handbook of Social Psychology: Group Processes* (pp. 182-208). [doi:10.1002/9780470998458.ch8]

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.

SCHWARZ, G., & Mosler, H. J. (2005). Investigating escalation processes in peace support operations: An agent-based model about collective aggression. In K. G. Troitsch (Ed.), *Representing Social Reality* (pp. 191-197). Koblenz: Fölbach

SCHWEINGRUBER, D., & Wohlstein, R. T. (2005). The madding crowd goes to school: Myths about crowds in introductory sociology textbooks. *Teaching Sociology Compass*, *33*, 136-153. [doi:10.1177/0092055X0503300202]

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).

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. (1976). *Administrative behavior: a study of decision making processes in administrative organizations*. New York: Harper.

STILL, K. (2000). *Crowd Dynamics*. PhD thesis. University of Warwick.

STOTT, C., & Reicher, S. (1998). Crowd action as intergroup process: Introducing the police perspective. *European Journal of Social Psychology*, *28*, 509-529. [doi:10.1002/(SICI)1099-0992(199807/08)28:4<509::AID-EJSP877>3.0.CO;2-C]

TARNOW, E. (1996). Like water and vapor--conformity and independence in the large group. *Behavioral Science*, *41*, 136-151. [doi:10.1002/bs.3830410204]

THERAKOMEN, P. (2001). *The experiments for exploring dynamic behaviors in urban places*. Master thesis. University of Washington.

VAN DE SANDE, H. (2006). *On Crowds*. (Unpublished)

VAN VLIET, T., & de Bruin, R. (2007). Enhancing peacekeeping operations with NLWs. Presented at the 4th European Symposium on Non-Lethal Weapons, Ettlingen, Germany.

WADDINGTON, D., Jones, K., & Critcher, C. (1989). *Flashpoints: studies in public order*. London: Routledge.

WAHBA, M. A., & Bridwell, L. G. (1976). Maslow reconsidered: A review on the need hierarchy theory. *Organizational behavior and human performance*, *15*, 212-240. [doi:10.1016/0030-5073(76)90038-6]

WETZER, I., Kamphuis, W., van Hemert, D., Huis in 't Veld, M & Kerstholt, J. (2010). Gedrag onder invloed van niet-letale middelen: twee veldexperimenten (Behaviour under the influence of non-lethal weapons: two field experiments). TNO Defence, Safety and Security. Confidential report (10 years).

WIJERMANS, N. (2011). *Understanding crowd behaviour*. PhD. thesis. University of Groningen, Groningen.

WILSON, R. A., & KEIL, F. C. (Eds.). (1999). *The MIT Encyclopedia of The Cognitive Science*. The MIT Press.