Understanding crowd behaviour

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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).