Understanding crowd behaviour

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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.

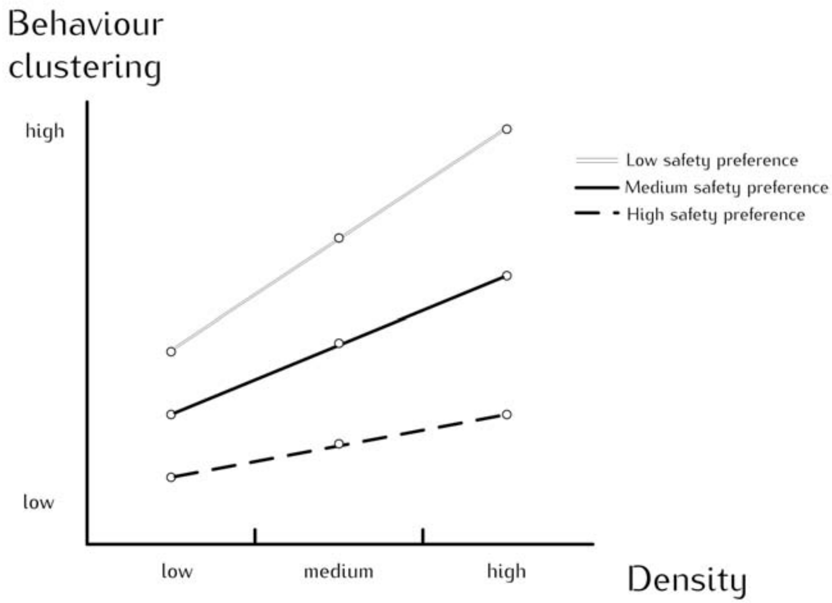

Figure 6.1: The expected relationship between density and behaviour clustering in a crowd for different levels of safety preference showing how a rise in density is expected to increase behaviour clustering, The higher the safety preference, the lower the level of behaviour clustering. The combination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

$$\text{ci(agent)} = \frac{agents-in-sight}{max-agents-in-sight};$$
$$\text{ciMean} = \text{mean(ci(allAgents))};$$

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

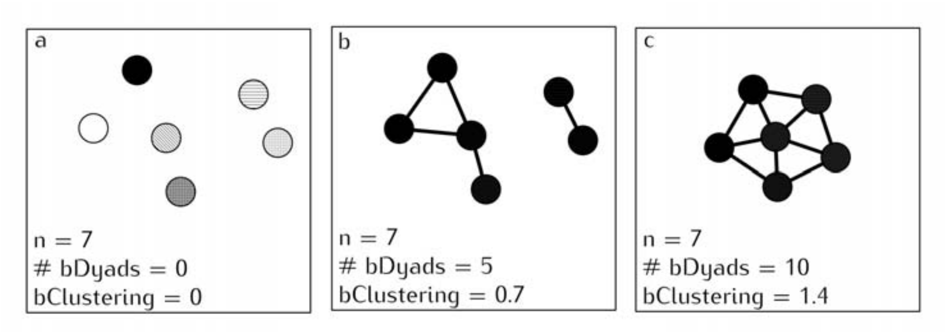

Figure 6.2: Behaviour clustering in a group represents a measure for behaviour patterns in a crowd. Behaviour clustering indicates to what extent agents that are in each others vicinity are behaving in the same way. a) shows agents that are all behaving differently (i.e. there is no behaviour clustering); 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.

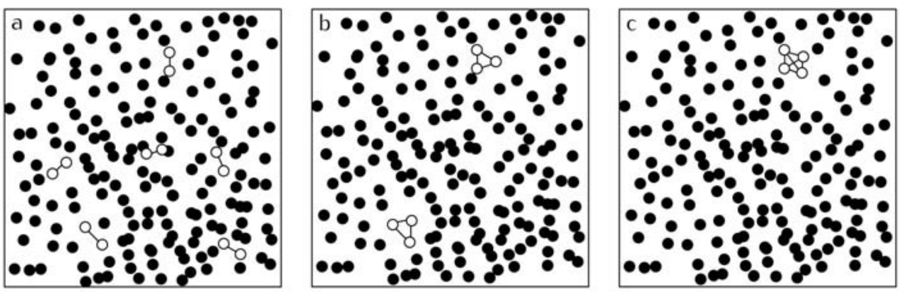

Figure 6.3: Behaviour clustering is a group level measure that represents the subgroups in a crowd in one number. This number gives a general impression of the behavioural patterns in a crowd on a scale from heterogeneous to homogeneous. The different situations that are visualised in a), b), and c) 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
Group level	Independent		Safety preference distribution [probability distribution]	Low = Beta(5,5) Medium = Beta(3,7) High = Beta(7,3)
Group level	Dependent		Behaviour clustering	$[0, n(n-1)/2]$
Individual	Life-history	inter	Clusterindex	$[0, 1]$
Individual	Life-history	inter	Behaviour	{walk,run,dance}
Individual	Life-history	intra	Arousal	$[0, 1]$
Individual	Life-history	intra	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

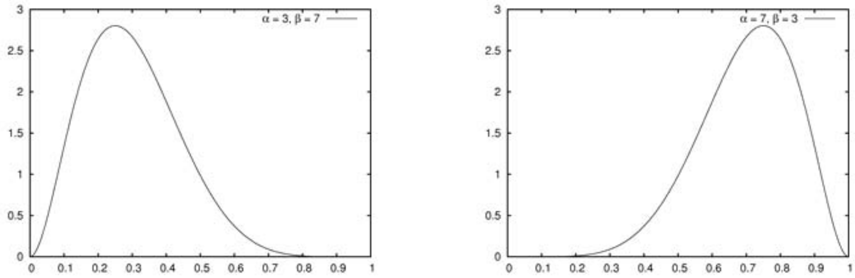

Figure 6.4: The agents' safety preference is set using a beta distribution. To represent the low safety preference distribution, the positively-skewed (beta(3,7)) distribution on the left is used. For the high safety preference distribution, the negatively-skewed (beta(7,3)) distribution on the right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

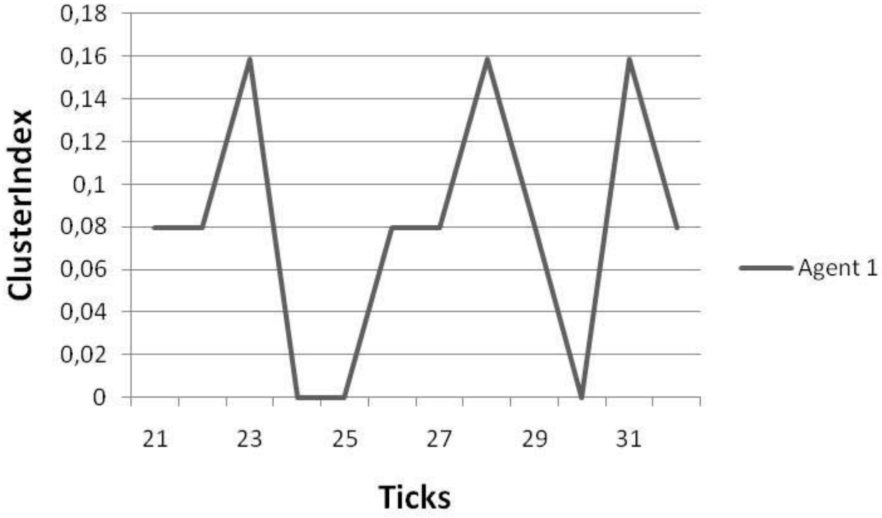

Figure 6.5: The local crowdedness that is perceived by Agent 1 between ticks 21-32. It illustrates that the environment of an agent changes, which affects what will influence Agent 1.

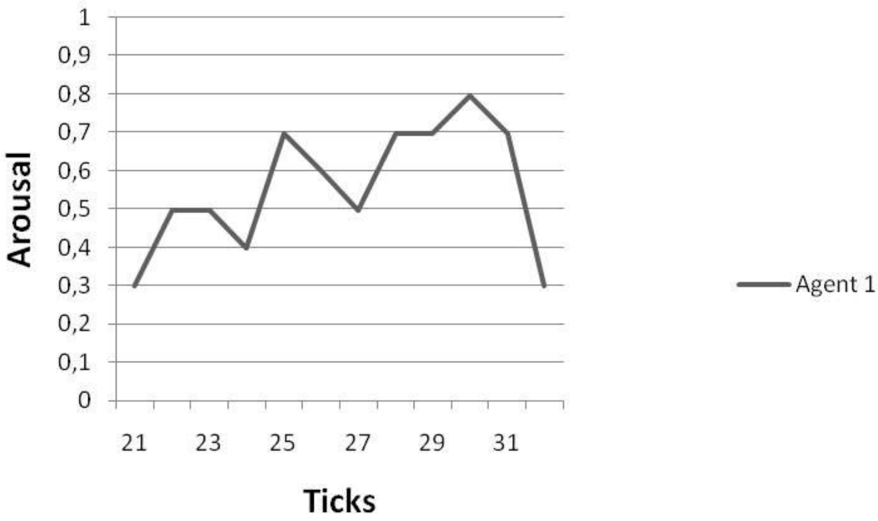

Figure 6.6: The arousal level of Agent 1 between ticks 21-32. It shows the fluctuations that are direct consequences of a changing local density [6] are shown.

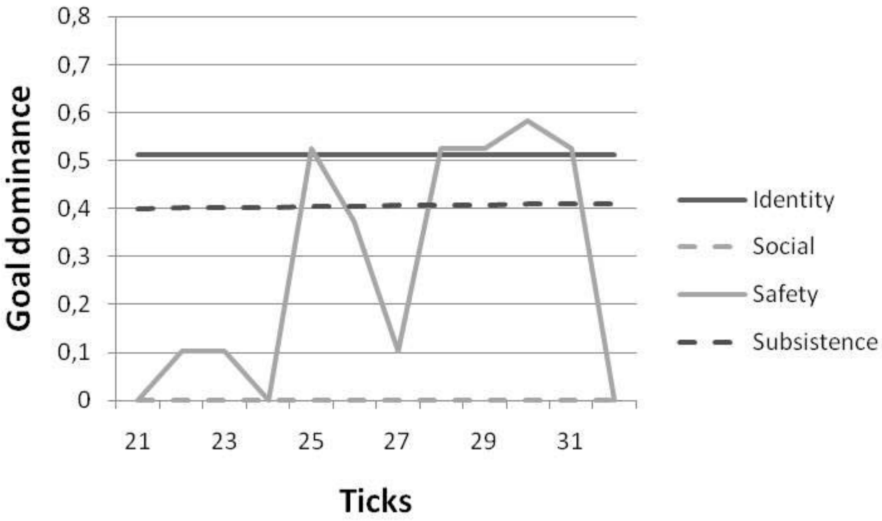

Figure 6.7: The goal dominance of the subsistence, safety, social, and identity goals of Agent 1 between ticks 21-32. The fluctuation of the safety goal dominance in particular is visible.

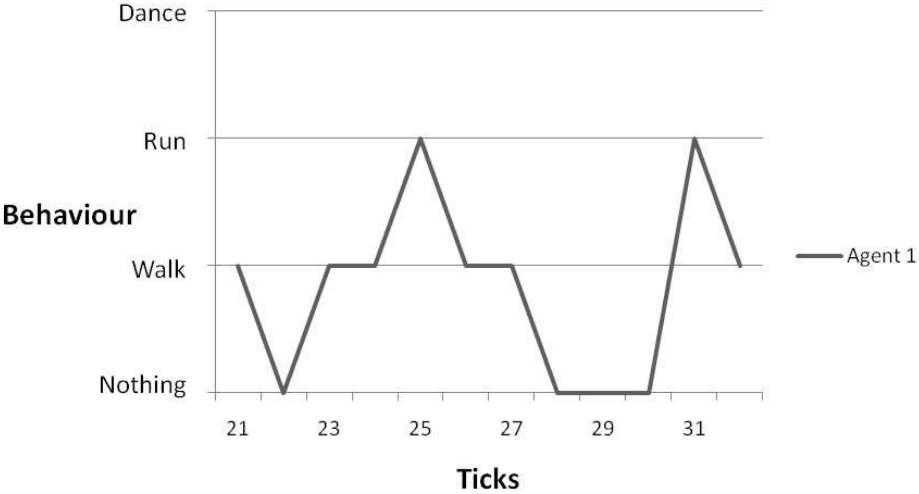

Figure 6.8: The behaviour that is exhibited by Agent 1 at each tick between tick 21-32.

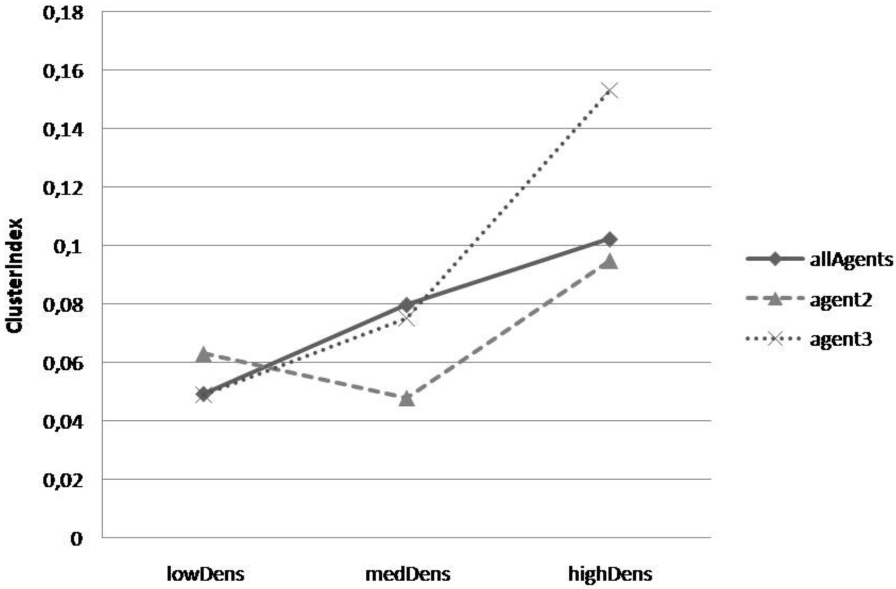

Figure 6.9: The cluster index (i.e. crowdedness) is related to the density level. In general, the cluster index rises as a consequence of a rise in density. When looking at individual agents, the cluster index may differ from the average.

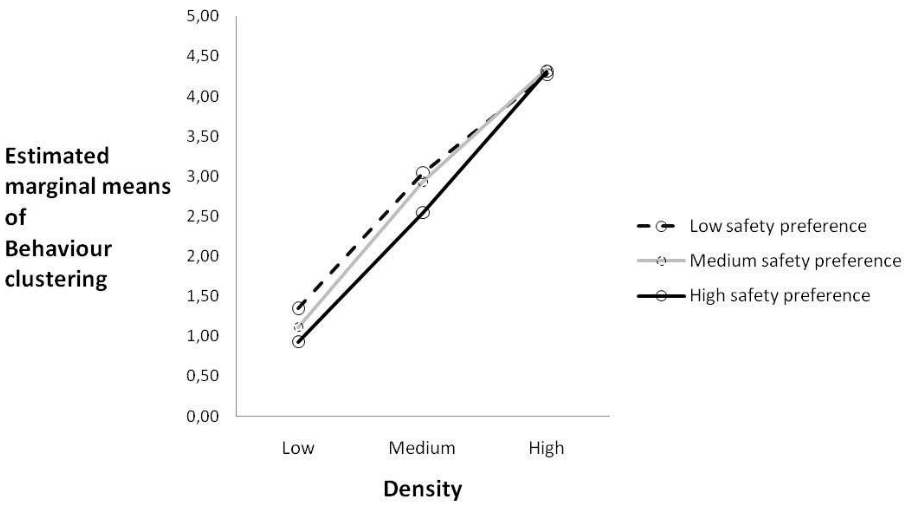

Figure 6.10: The estimated marginal means of behaviour clustering, visualised for all nine conditions.

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).

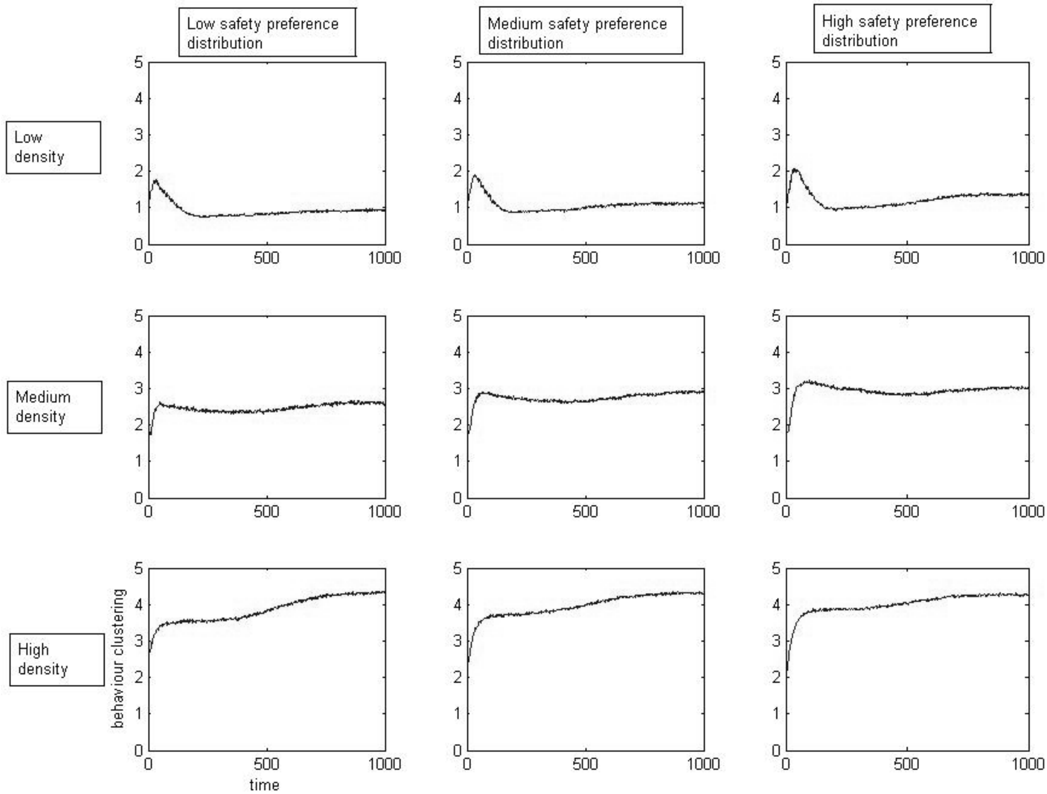

Figure 6.11: An overview of the behaviour clustering average for all conditions over 30 runs. The density levels (low, medium, high) are represented in the rows. The varying safety preference distribution(low, medium, high) is presented in the columns.

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.