ESCAPES - Evacuation Simulation with Children, Authorities, Parents, Emotions, and Social comparison

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ABSTRACT

In creating an evacuation simulation for training and planning, realistic agents that reproduce known phenomenon are required. Evacuation simulation in the airport domain requires additional features beyond most simulations, including the unique behaviors of first-time visitors who have incomplete knowledge of the area and families that do not necessarily adhere to often-assumed pedestrian behaviors. Evacuation simulations not customized for the airport domain do not incorporate the factors important to it, leading to inaccuracies when applied to it.

In this paper, we describe ESCAPES, a multiagent evacuation simulation tool that incorporates four key features: (i) different agent types; (ii) emotional interactions; (iii) informational interactions; (iv) behavioral interactions. Our simulator reproduces phenomena observed in existing studies on evacuation scenarios and the features we incorporate substantially impact escape time. We use ESCAPES to model the International Terminal at Los Angeles International Airport (LAX) and receive high praise from security officials.

Categories and Subject Descriptors

I.6.3 [**SIMULATION AND MODELING**]: Applications

General Terms

Security

Keywords

Innovative Applications, Evacuation, Crowd Simulation

1. INTRODUCTION

From large-scale citywide evacuations to small-scale evacuations of buildings, emergency evacuations are unfortunately a perpetual fixture in society. Fire drills and other 'mock evacuations' generally used today fail to accurately prepare us for evacuations in which life-threatening danger is immediate and, in fact, are very often ignored altogether [5]. Thus, designing security policies based on them do not accurately account for actual human behavior. Simulations can provide an additional method of evaluating security policies that gauge the impact of different environmental, emotional, and informational conditions. In any evacuation, the layout of the area, the population composition, level of urgency, and the behavior of authority figures all play a role in the safety and speed of an evacuation. The ESCAPES system is a multiagent evacuation simulation tailored to the needs of airport security officials based on existing psychological and evacuation research.

Office buildings and railway stations, which are often the subject of evacuation studies, possess largely homogenous crowds of business people that are very familiar with the environment. Airports, however, have a large presence of families and first-time visitors which are major considerations for security officials [3]. Families present a completely different model of human behavior, as they no longer follow the often-assumed 'self-preservation first' edict and often seek to ensure the safety of family members first [19]. Travelers' uncertainties about the environment logically lead to increased reliance on authority figures for directions and necessitates a realistic model of information-spread about events and exits as well as a model of behavior when no exit locations are known.

These features that officials have identified as especially important to airport evacuations have not been specifically addressed by existing commercial and academic simulators. Legion Software[1], for example, is used by security forces in many areas to evaluate the expected speed of traffic flow through an area. However, it does not model agent types such as families and authority figures or realistic knowledge spread about the environment and events. Other evacuation simulators in academia explore more detail and even base their agents on psychological models, such as Pelechano et al. [18]. However, their work does not model the behaviorial dynamics unique to family units, nor the emotional contagion of the crowd as fear levels rise during the evacuations.

In our meetings with security experts affiliated with Los Angeles International Airport, they discussed the importance of agent types, the presence of fear, and realistic knowledge spread. In addition, a

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[1] www.legion.com

Phenomenon	Ref.	Feature
People forget their entrance	[2]	Misc.
First-time Visitors	[3]	SoK / SCT
Heightened emotions -> chaos	[21]	Emotions / EC
Herding behavior	[10]	SCT / Families
Pre-evacuation delay	[4, 14]	SoK / Families
Families gather before exiting	[19]	Families
Authorities calm people	[21]	Auth / Emotions

Table 1: Phenomena modeled in ESCAPES

strong 3D visualization was emphasized for the purpose of visual conditioning during security personnel training. Thus far, airport security officials have been forced to use general simulations to answer questions about authority figure placement, number, and policy. Our work aims to fill this gap by tailoring a system to the particular needs of an airport evacuation and other similar scenarios with a solid grounding in psychological and evacuation research.

We discuss our multiagent evacuation simulation system, ESCAPES, in two parts: individual agent types and agent interactions. ESCAPES includes regular travelers, authority/security figures, and families, as these have been documented as having the most impact in an airport evacuation [3]. Another major aspect of evacuations is fear. Although there is substantial debate on the existence of 'panic' in evacuations, the presence of fear is undisputed [20]. For the purposes of our work, we focus on a baseline implementation of fear and its impacts. Finally, in discussions with airport security officials, incomplete knowledge of the environment was cited as a major concern. Thus, we also give agents incomplete knowledge of the world by restricting their knowledge of the exits and the event causing the evacuation.

ESCAPES agent interactions include three separate phenomena: spread of knowledge, emotional contagion, and social comparison. Evacuation literature shows that the crucial seconds people spend before actively moving towards an exit greatly impact their survivability and is largely due to uncertainty about the nature of the evacuation [4]. Thus, we include a 'Spread of Knowledge' (SoK) component, which realistically models the spread of information about an event and that an evacuation is truly necessary. Emotional Contagion (EC) is the well-documented phenomena that causes one person's emotional state to be impacted by neighboring people's emotional state [9]. We incorporate EC in our system as a logical byproduct of our inclusion of fear in the presence of crowds. Finally, in a situation where people don't have all the information, following others is a commonly seen phenomenon. Social Comparison Theory (SCT) is a theory of how one person impacts another at a broad level, positing that people perceived to be similar to each other will mimic each other [6]. We use SCT to direct people's actions when they have no knowledge of the environment.

Existing evacuation simulations fail to take these factors into account in a cohesive fashion, resulting in visually appealing but ultimately inaccurate simulations of airport evacuations. In ESCAPES, we model agents based on key features identified by LAX officials and attributes from evacuation literature and explore the impacts of these factors on the speed and smoothness of evacuation. In particular, we include emotions that impact behavior, authorities, family units, realistic spreading of knowledge about an emergency, emotional contagion, and social comparison. We describe each of these components in more detail in Sections 3 and 4 and explore their impacts on evacuations in great depth in Section 5. We show that inclusion of these factors leads to a number of emergent behaviors documented in literature, as summarized in Table 1. Finally, we conduct tests on a model of a terminal at Los Angeles International Airport and begin to provide answers to security officials' questions about authority figure policies.

2. RELATED WORK

Early work in pedestrian dynamics noted the similarity between crowd behavior and well-understood phenomena observed in physics. These observations led to the development of models based on fluid-dynamics [12]. Another approach to force-based crowd simulation is built off the idea of social forces [11]. Instead of being based on the physical properties of water or gas, social forces represent the attractive and repulsive forces felt by a pedestrian toward various aspects of its environment. Yet another approach involves the use of cellular automata (CA). In CA-based models [1], the environment is divided into a grid consisting of cells. At each time step, a cell transitions to a new state based upon its current state and the states of the neighboring cells. However, in both forced-based and CA-based models, it is difficult to simulate goal-driven and heterogeneous behavior. Thus, the specific crowd phenomenon we are looking at are not typically modeled with these approaches.

Agent-based models allow for each pedestrian to be modeled as an autonomous entity. Under this model, pedestrians are represented as agents capable of perceiving and interacting with their environment as well as other agents. While being the most computationally expensive modeling technique, agent-based models are capable of a higher degree of expressivity and fidelity. The ability to represent cognitive information and model complex and heterogeneous behaviors has opened the possibility for new avenues of research that had not been attempted with previous methods.

As a result, there has been a shift toward the use of agent-based models for evacuation simulations. However, much of this research has been focus solely on modeling the physical interactions between agents[16]. The EXODUS[2] system represents the state-of-the-art for these systems with versions specifically for various types of large-scale scenarios and additional modules that can model phenomena such as toxic gas and fire spread. The system does move slightly beyond physical interactions to include informational aspects such as signage and exit familiarity, but still does not attempt to use psychologically-based decision-making in their agents.

Despite this trend, there has been some interest in incorporating emotional as well as the informational interactions into agent-based models. The complex relationship between the spread of information and the spread of emotion was explored from a theoretical modeling perspective in [13]. [17] focuses on creating agents with sophisticated psychological models. Our research is less concentrated on individual agents and more concerned with the interactions between agents and the resulting group dynamics. Additionally, ESCAPES is focused on a different set of domains including airports, malls, and museums. To accurately represent these types of environments, we believe it is particularly important to model the influence of families, emotional contagion, social comparison, and spread of knowledge, which past work has not cohesively addressed.

3. AGENT DESIGN

The ESCAPES system is a two-part system comprised of a 2D, OpenGL environment based in the open-source project OpenSteer[3] and a 3D visualization component using Massive Software[4]. The

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[2] http://fseg.gre.ac.uk/exodus

[3] http://opensteer.sourceforge.net

[4] http://www.massivesoftware.com

2D module consists of agents as described below, outputting their physical and behaviorial information into files that are then imported into customized Massive extensions to generate 3D movies of the scenarios. The 2D module can be used for efficient statistical analysis of different security policies. As mentioned previously, the 3D visualization is a key component for airport security officials, as it provides a superior training medium to their current tools. Screenshots in Figure 3 show the children models as well as some people running in different directions (denoted in the white circle) when an evacuation begins. Here we describe the architecture of the 2D module, first introducing the individual traveler agent, then detailing two special agent categories (families, authorities), and finally discussing interaction level dynamics (spread of knowledge, emotional contagion, social comparison).

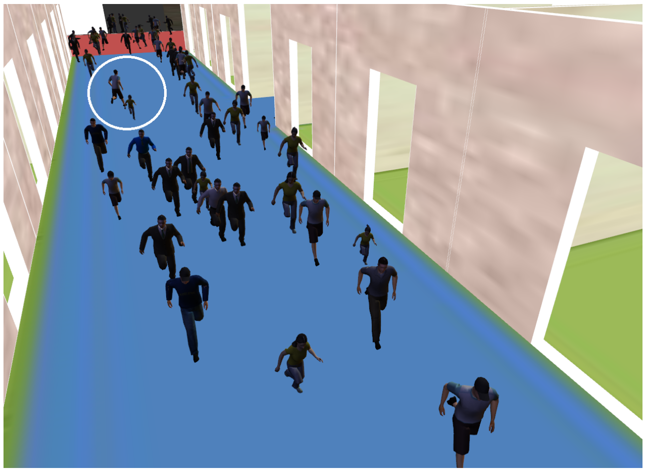

Figure 1: ESCAPES 3D visualization

3.1 Individual Travelers

All agents share a common architecture based in a BDI framework, possessing varying degrees of knowledge about the world and their neighbors. Each agent has access to a subset of the 14 available behaviors, any one of which may be active at a given time, where the behavior is selected via a probabilistic weighting scheme. The weighting scheme is a combination of 6 'Cognitive Mechanisms,' each of which prioritize some of the agent's desires. For example, there is a Cognitive Mechanism that prioritizes the basic desire of an agent to 'Wander' through his environment or 'Shop' in the stores. On the other hand, we have another Cognitive Mechanism that prioritizes an agent's desire to survive by evacuating through an exit once an event has occurred via one of the escape behaviors ('Run to Nearest Exit', 'Run to My Exit', and 'Search for Exit'). During execution of these behaviors, individual travelers may move at integer speeds from 0 to 3.

Each agent also has specific levels of emotions and information about the environment. Studies have shown that emotional stress causes changes in decision-making and may even cause someone to forget where he/she entered a building from [2]. Combined with the incomplete knowledge of a person that is in a place for the first time, which occurs extremely frequently in the airport scenario that we model, an evacuation suddenly becomes much more difficult to manage. Thus every agent has a fear level, an event certainty level, as well as a list of known exits. A more extended discussion of these attributes will take place in Section 4, but we briefly mention their implementation here first.

Fear is modeled as an integer value between 0 and 2 (*FearFactor*), 0 indicating that the agent has no fear. Higher levels of fear lead to higher movement speeds to get out of the area as soon as possible. Each agent's fear is a result of a number of factors such as their proximity to the event, the presence of authority figures nearby (as a result of documented impact of authority figures on evacuees [3, 21]) and the level of fear in neighbors and family members (as a result of Contagion [9]).

Event certainty is modeled as an integer value between 0 and 2 (*EventCertainty*), designating how aware the agent is that an event has occurred and that, therefore, an evacuation is necessary. An event certainty level of 2 is generated only by people close to the event, who immediately run directly away from the event before beginning active exiting behavior. Further away agents may have 1, which immediately triggers exiting behavior. Agents furthest away have an EventCertainty of 0 and continue their normal behavior, as they are unaware of any need to evacuate. Each agent's EventCertainty level is dictated by their proximity to the event, the presence of authority figures nearby that would inform them of the event, and the event certainty of neighbors via the Spread of Knowledge mechanism discussed in Section 4.1. The importance of uncertainty about an event has been noted in evacuation literature as a major cause of delay and, therefore, casualties [4].

Exit knowledge is modeled as a binary value indicating whether or not an agent knows about a given exit. Given a list of known exits, if an agent decides to evacuate, he will choose the nearest one. Exit knowledge is dictated by where they entered from, a random chance to forget that exit, and the presence of authority figures nearby that would inform them of exits. A person's knowledge of exits are clearly of paramount importance in any evacuation situation, especially in airport scenarios where many people are first-time visitors and are unaware of the environment layout.

3.2 Family Agents

Evacuations in some environments pose additional challenges as a result of the population present. In the airport scenario that we focus on, families have been identified as an important facet of the environment that must be modeled to more realistically portray the situation [3]. One can see how this might differ from the evacuation of an office building where only knowledgeable adults are present. For instance, children often rely on their parents to lead them and parents will undoubtedly seek out each other and their children before exiting, oftentimes disobeying authority instructions [19].

We model the presence of family units composed of 2 parents and 2 children with behaviors and cognitive mechanisms not applicable to general agents. Prior to an evacuation, children usually execute the 'Follow Parent' behavior, except occasionally executing the 'Drag into Shop' behavior which leads their parents into nearby stores that they find interesting. To enhance realism, we also restrict children to slower movement speeds (maximum of 2), which parents leading them will inevitably match. Parents that are not with their children heavily prioritize finding them via the 'Find Child' behavior, and put some emphasis on the 'Find Other Parent' behavior (they may also Wander or Shop). When an evacuation occurs, however, parents immediately seek each other out to gather the family together before proceeding to an exit, as has been shown to occur in real evacuations [19]. After an evacuation is underway, children will no longer execute the 'Drag into Shop' behavior, resorting exclusively to 'Follow Parent'.

3.3 Authority and Security Agents

Studies have shown that some authority figures have a very strong calming effect on people in an evacuation situation [21]. This can come through implicit calm at the sight of other people that appear calm via emotional contagion and may be enhanced due to the uniformed authorities having a stronger contagion effect due to their leadership role [9]. Also, by simply being there everyday, authorities know the environment and are trained to properly direct people to the nearest exits in the event of an emergency.

In our simulator, under normal conditions, authority agents 'Wander' or 'Patrol' the environment. After an event occurs that necessitates an evacuation, all authority figures switch to 'Patrol' in an attempt to inform everyone of the event and where nearby exits are located. We also set the FearFactor of authority figures very low and keep it constant to mimic well-trained security personnel that can maintain a level head in volatile situations. The calming effect they have on other agents is modeled by overriding nearby agents' FearFactor with the authority figure's FearFactor. The practical effect of this is to slow agents down (since FearFactor directly impacts travel speed), which may increase the total evacuation time, but also reduces the severity of colliding and the level of chaos. Also, authorities know all exit and event locations and pass this information to agents that are nearby.

4. AGENT INTERACTIONS

With the existence of crowds, agent interactions are a fundamental aspect of our evacuation simulation. Thus, we base our agent interactions on existing evacuation and social psychology research. We incorporate a realistic 'Spread of Knowledge' of events and exits, an Emotional Contagion module to model the infectious nature of emotions, as well as a social comparison component to capture people's mimicry of others.

4.1 Spread of Knowledge

As mentioned, while unimportant for office building or railway station simulations, realistic knowledge spread to model the behavior of first-time visitors is a necessary component in an airport simulation. Thus, we model the spread of two types of knowledge in our system: Exit Knowledge and Event Knowledge.

4.1.1 Exit Knowledge

People entering an environment for the first time will possess incomplete knowledge of exit locations. Thus, they must rely on authorities, signs, and following the crowd to make their way towards the nearest exit if there is one closer than the one they entered from. It has been shown that in times of high emotional stress, people even forget where they entered [2].

Our simulator includes this level of realism, giving agents knowledge of their entry location and a random chance that they forget this knowledge. In contrast, authority figures begin with and maintain full knowledge of all exit locations and pass a limited subset of this to nearby agents to simulate their redirection of passersby to the nearest exits. Also, family members will inform each other of exits they find out about, but otherwise, agents do not communicate exit knowledge to each other. Agents are also able to use the 'Search for Exit' behavior to find a way out on their own or some may choose to simply follow nearby, similar agents via the SCT module's 'Follow Most Similar Agent' behavior.

4.1.2 Event Knowledge

In real emergency situations, pre-evacuation delay has been cited as a major cause of slower evacuations and, therefore, deaths [4, 14]. This delay is largely due to a lack of knowledge about the emergency, both in disbelief of the severity of the situation as well as a desire to find out more about what has occurred. Pre-evacuation delay has been noted to persist despite verbal warnings and physical cues in the environment [14].

In our simulation, agents that are near the event as it occurs will have full knowledge of what has occurred, whereas agents far away have no idea are unaware that anything is wrong. As civilians pass each other, they communicate their level of certainty to each other, raising awareness of the situation. As civilians become more aware, they are more likely to run towards the exit as their self-preservation desires take precedent over all other desires.

Authority figures are assumed to instantly know when something has occurred, simulating an immediate radio notification from central security personnel. This does not necessarily translate into an immediate announcement to the general public, since oftentimes the appropriate response is not immediately obvious. Authority figures also communicate their certainty of the event to nearby agents, mimicking an actual authority figure telling people to evacuate.

4.2 Emotional Contagion

Emotional contagion is the effect of one person's emotional state on the emotional state of people around him/her both explicitly and implicitly [9]. It has been observed in families, small-scale interactions as well as large crowds [7, 9]. Researchers continue to develop theories on the phenomenon and are still exploring the various factors that are believed to influence the level of contagion as well as its effect on decision-making.

In an evacuation scenario, fear abounds, due both to uncertainty of the situation as well as concern for one's own safety [21]. As a result of emotional contagion, bystanders that are unaware of the event may develop otherwise inexplicably high levels of fear as well. Their subsequent decisions and behaviors as a result of this 'inherited' fear have not been explored in the context of a crowd or evacuation simulation. We therefore propose a baseline implementation and analysis of a model of emotional contagion.

Specifically, we have two components that spread emotions amongst agents. First, as agents pass by each other, they inherit the highest level of fear of neighboring agents. This is the baseline emotional contagion model that conforms with a theory of emotional contagion in which the highest level of emotion is transferred to all surrounding agents and inherited at full effect [9]. Second, as agents pass by authority figures, their level of fear is reduced to the authority figure's fear level. This simulates the implicit and explicit calming effect of authorities and conforms with a theory of emotional contagion that allows for specific agent types to reduce the level of emotion of surrounding agents (e.g., an agent that is greatly respected by all surrounding agents [9]).

4.3 Social Comparison (SCT)

Social Comparison Theory [6] is a social psychology theory, initially presented by Festinger. It states that humans, when facing uncertainty, compare themselves to others that are similar to them, and act towards reducing the differences found. Social comparison is considered a general cognitive process, which underlies human social behavior. During emergencies, individuals face greater uncertainty, and thus the weight of social comparison in human decision-making is increased [15].

We find the utilization of the computational model of social comparison [8] helpful in developing agents with the social skills that are crucial to the accurate simulation of different crowd behaviors. The SCT computational model can be used, for instance, by agents who wish to urgently exit an area. If they do not know the location of a close exit, they may turn to mimicking others hoping that they will lead them to safety.

For the simulation, SCT was implemented as follows. First, the agent compares itself to others around it by measuring the similarity in a set of features, including speed, emotional state, distance, etc.. The similarity values are combined, and the agent that is most similar (within bounds) is selected. The agent executing SCT takes actions to reduce dissimilarities to the selected agent. In this simulation, SCT increases the tendency to mimic someone else's behavior, whereas emotional contagion transfers emotions regardless of what different behavior will be chosen based on it.

5. EVALUATION

We conducted extensive testing using a generic scenario to evaluate the impact of the emotional and informational phenomena modeled in ESCAPES. The scenario takes place in a generic airport setting consisting of 2 gates, 3 hallways, and 14 shops. There is an exit in each gate as well as the end of one of the hallways. Unless otherwise noted, the experiments for the generic scenario feature the following: 100 travelers which includes 10 families, 10 authority figures, emotional contagion, spread of knowledge, and social comparison. Simulated evacuations are typically evaluated by examining the rate at which people evacuate. While, evacuation rate is obviously important there are other metrics which can also provide insight as to how an evacuation proceeded. In Sections 5.1-6, we analyze the results from these experiments using the metrics which best highlight the effect of the various phenomena. Additionally, we modeled Tom Bradley International Terminal at Los Angeles International Airport and ran proof-of-concept tests on this to evaluate our performance on a real domain. A description of the scenario and accompanying results is provided in Section 5.7

In all of our experiments, an event occurs during the 14th time step and travelers have until the 300th time step to evacuate. It is assumed that by this time, airport officials will have managed to coordinate in response and issue a general order to evacuate through their emergency broadcast system. All the results in this section have been averaged over 30 independent simulations.

5.1 General Testing

As mentioned in previous sections, current evacuation simulators tend to focus on the physical interactions of agents. The agents in these simulations are typically homogeneous, rational, and omniscient. In contrast, ESCAPES agents are heterogeneous, emotional, and limited in both knowledge and perception. In Figure 2, we compare the evacuation rates from simulations in which the population of travelers is modeled as homogeneous, omniscient agents to those in which the population is modeled as ESCAPES agents including authority figures and families. The y-axis represents the percentage of travelers who have yet to evacuate. This percentage will decrease over time and the slope of the line signifies the current rate at which travelers reached safety. For example, after 85 time steps we can see all travelers have evacuated in the physical interaction model whereas 25% of travelers have yet to evacuate in the physical, emotional, and informational model.

When modeling omniscient agents, simulations consist of travelers with complete knowledge who are not influenced by their emotions. The only relevant interaction between travelers occurs when there is congestion due to an area becoming overcrowded. When the event occurs, all travelers are able to perceive it instantaneously and begin to head for an exit. We see a steep decline in the number of unevacuated travelers, as those close to an exit evacuate rapidly. There is then a temporary decrease in the rate of evacuation as those travelers who were far away from an exit rush towards it. Once those travelers start reaching the exits, the rate of evacuation picks up again until everyone has evacuated. While these models can provide a good first order approximation, they fail to capture much of the underlying complexity present in evacuations.

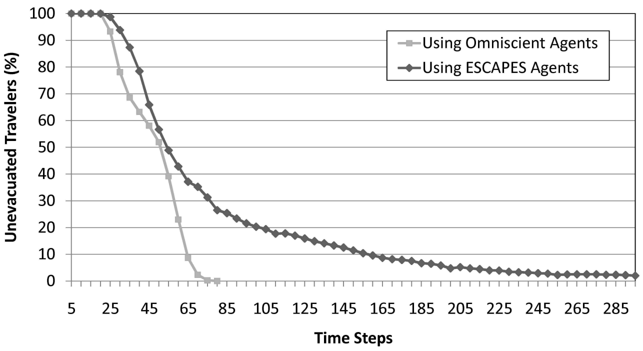

Figure 2: Effect of Modeling Physical, Emotional, and Informational Interactions on Evacuation Rate

With travelers who are more realistic, the evacuation rate is slower. This is due to a multitude of factors such as families taking time to find their loved ones, travelers never learning about the event, or travelers having limited knowledge about exits. Unlike when travelers are modeled as omniscient agents, situations arise with ESCAPES agents where there are travelers who are unable to evacuate in time. However, it is important to examine these situations because it is exactly these scenarios where the potential for danger is greatest were they to occur in real life. Models using omniscient agents provide best-case scenarios and a lower bound on evacuation times. While this information is useful, a system that is capable of modeling unforeseen worst-case scenarios, such as ESCAPES, will be more effective as a training and policy-making tool.

5.2 Families

Studies have shown that the presence of the families results in slower evacuation times [19]. We tested the effect of families on evacuation rate by comparing the results from simulations with varying numbers of families. Figure 3 shows that increasing the number of families slows the overall rate of evacuation. After 85 time steps, simulations starting with 10 families had 30% of travelers remaining, whereas the simulations with 5 families had 15% remaining, and simulations with no families had only 5%. This slow down is a consequence of two main factors. First, instead of heading towards a known exit immediately upon learning of the event, parents first seek out the other members of their family. As a result, parents will often ignore known information and perform actions which are suboptimal from an individual perspective. Second, once family members have found each other, they stay grouped together. Due to children moving more slowly, as mentioned in Section 3.2, family units move slower than typical travelers.

5.3 Emotional Contagion

The spread of emotions through crowds as a result of emotional contagion has been well-documented [9]. In the simulations, emotional contagion is used to propagate fear. Travelers with high levels of fear pass on their FearFactor to travelers with lower levels of fear. Higher values of FearFactor activate a flight response in travelers. At the crowd level, this phenomenon causes travelers to collide into each other. The overall number of collisions can then be view be as a measure of the level of chaos in an evacuation. By modeling emotional contagion, we would expect to see an increased levels of fear which in turn will produce a higher number of collisions between travelers.

To isolate the impact of emotional contagion we ran experiments

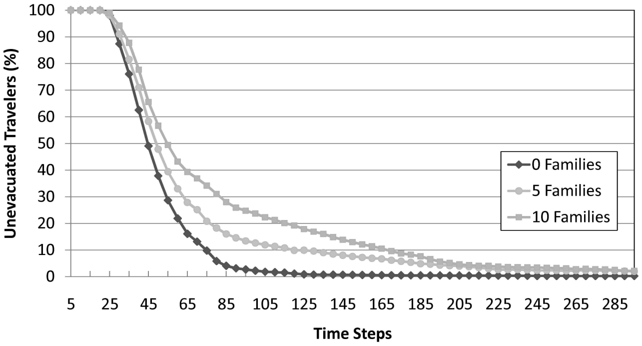

Figure 3: Effect of Families on Evacuation Rate

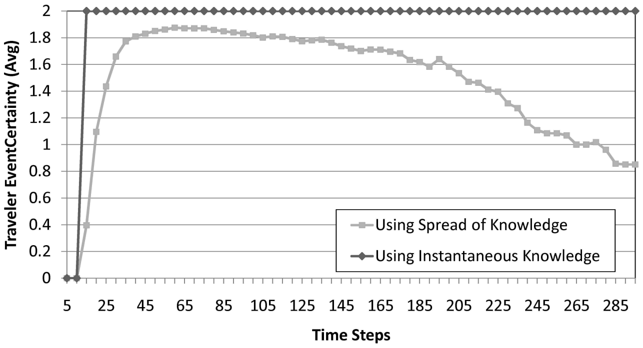

Figure 4: Effect of Knowledge Tranfer on EventCertainty

without authority figures. Without the calming influence of authority figures, there is nothing to impede the dissemination of fear through emotional contagion. Specifically, we compared the number of high-speed collisions that occurred over the course of an evacuation both with and without emotional contagion. High-speed collisions are defined as collisions that occur while a traveler has a speed of 2 or greater. Focus is placed on these collisions as they are more likely to cause injury or falls in real evacuations. When emotional contagion is modeled, evacuations average 6932 high-speed collisions, whereas evacuations without emotional contagion average 2701 high-speed collisions. From these results, we can see that modeling emotional contagion results in more chaotic evacuations with an increased number of high-speed collisions.

5.4 Spread of Knowledge

Agent-based evacuation simulations often start after an incident has occurred and assume that all agents are instantaneously aware of the need to evacuate. ESCAPES is geared towards domains where this is likely not the case. It is then important to model how knowledge of an event would spread throughout a crowd. In the simulations, EventCertainty represents the level of a traveler's knowledge of the event. Higher values of EventCertainty reflect greater knowledge about the event. The average EventCertainty over all unevacuated travelers is a good way to measure the level of knowledge of those who are still in danger.

In Figure 4, we contrast our model for the spread of knowledge against a model in which instantaneous knowledge is assumed. The y-axis represents the average EventCertainty for all unevacuated travelers, while the x-axis represents the time step. With instantaneous knowledge, travelers are able to fully perceive the event immediately after it occurs regardless of where they are situated in the environment. Accordingly, the average EventCertainty jumps from 0 (no knowledge) to 2 (full knowledge) and remains at this level for the duration of the simulation. When knowledge is spread, the situation is much different. Immediately after the event, EventCertainty is low as only the travelers close by know that is has occurred. As time passes, knowledge of the event propagates through the crowd as travelers with information disseminate it to their neighbors. As a result, EventCertainty rises until it reaches a point where almost all travelers are fully aware of the event. From this point, EventCertainty decreases as travelers with knowledge of the event are able to evacuate leaving an increasingly higher proportion of travelers who are unaware of the event.

Throughout the evacuation, authority figures are patrolling for travelers to inform. However, if a traveler is particularly isolated they may never come into contact with an authority figure. Instantaneous knowledge is a common assumption in agent-based evacuation models, but humans are not omniscient. In comparison, our model for the spreading of knowledge provides a more realistic approximation of knowledge diffusion through crowds.

5.5 Authorities

Authority figures have been shown to exhibit a calming effect over crowds [21]. In the simulations, authority figures always have a low level of fear (FearFactor=1) and the highest level of knowledge about the event (EventCertainty=2). They then help to calm the crowd by passing these values onto all travelers they come into contact with. Thus, the presence of authority figures in the simulations should result in a lower level of fear among travelers. We can use the percentage of unevacuated travelers with the highest level of fear (FearFactor=2) as an inverse measure on the ability of authority figures to calm the crowd.

Figure 5 shows the effect of varying the number of authority figures on the FearFactor of travelers over the course of the evacuation. The y-axis represents the percentage of unevacuated travelers with FearFactor=2. Initially, there are no travelers with FearFactor=2. At the 15th time step, the percentage increases to include all travelers close to the event. This percentage continues to climb as a result of the contagion effect until it reaches a maximum between the 35th and 50th time steps. As time progresses, the effect of emotional contagion is balanced out by the influence of authority figures and the successful evacuation of travelers with FearFactor=2. From the results, we can see that increasing the number of the authority figures results in a lower percentage of travelers with FearFactor=2. With 6 authority figures, the percentage of travelers with FearFactor=2 reaches a maximum of 47%, whereas simulations with 8 and 10 authority figures reach maximums of 36% and 27%, respectively. Given that authority figures are distributed evenly, this is a logical result, as more authority figures provide for better spacial coverage. This in turn, increases both the likelihood and speed in which authority figures will inform travelers about the event. Thus, we have shown that authority figures in the simulations display a calming effect on travelers and increasing the number of authority figures only strengthens this effect.

5.6 SCT

It has been observed that Social Comparison leads people in close proximity to mimic the actions of the those around them [6]. In a crowd setting this would logically result in a grouping effect. The phenomenon of grouping within crowds has been well documented in research on pedestrian dynamics [10]. To measure the prevalence of localized grouping in the simulations, we introduce the notion of connectivity. A traveler's connectivity is equal to the number of neighboring travelers plus one. Travelers are considered to be neighbors if they are within a specified distance of each other.

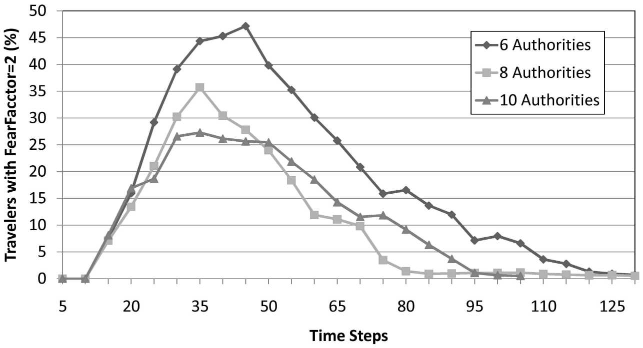

Figure 5: Effect of Authority Figures on FearFactor

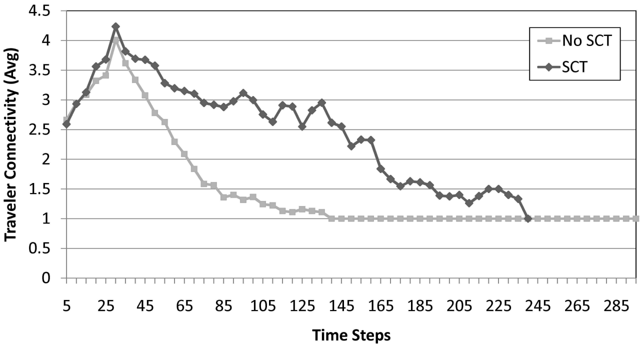

Figure 6: Effect of SCT on Connectivity

Thus, a traveler with a connectivity of 1 is considered to be isolated. As connectivity is a measure of grouping, we would expect to see an increase in the overall level of traveler connectivity by modeling Social Comparison. The impact of Social Comparison on the average connectivity of all unevacuated travelers can be seen in Figure 6. Connectivity, both with and without Social Comparison, rises in the moments leading up to and following the event. Without Social Comparison, the level of connectivity then steadily drops as travelers begin to disperse and exit the terminal. This continues until the average level of connectivity reaches 1, which represents travelers being isolated. With Social Comparison, the level of connectivity declines at a much slower rate before also reaching 1. These results indicate that Social Comparison increases the level of connectivity and thus the amount of grouping displayed by travelers.

5.7 Los Angeles International Airport

Finally, we modeled the Tom Bradley International Terminal (TBIT) at Los Angeles International Airport as a realistic test scenario for our simulation environment. The scenario is approximately 55 times larger than the test case used in Section 5. Ideally, we would have liked to experiment on the full scenario and compare results with data from LAX, however, such data is not available. While lack of data is a major issue for most simulations in academia, the security domain presents an added level of difficulty due to confidentiality and national security concerns surrounding such data. Thus, for the tests in this section, we focused on one end of the terminal (the hallway and two gates, with one exit in each gate) and examined the impact of various authority policies with the aim of generating policy recommendations. We used 200 pedestrians, including 20 families of four, variable number of authorities, and two exits as the default case.

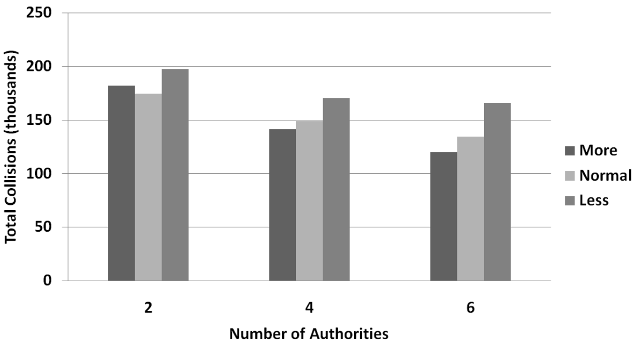

Figure 7: Effect of adding exits and authorities

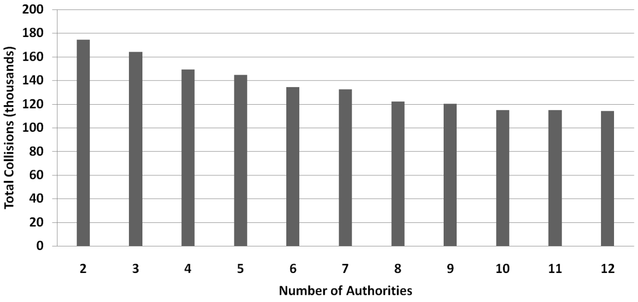

Figure 8: Effect of more authorities

As a baseline test, we first ran experiments to examine the impact of increasing the number of authority figures as well as removing one exit from the scenario. We would expect that increasing the number of authority figures creates a calmer evacuation and removing an exit creates a more chaotic evacuation as more people squeeze towards fewer exits. Figure 7 shows the number of collisions (in thousands) under different parameter settings, where the number indicates the number of authorities in the setup and More/Less indicates whether an exit was added or removed from the base scenario. Higher bars indicate a more chaotic evacuation. All differences within a single authority setting, with the exception of 2-authority More vs 2-authority Normal, were statistically significant. As can be seen by the fact that the results are higher as we move to the right within a single authority setting, fewer exits lead to more chaotic evacuations. Comparing across authority settings, all differences within a single exit setting were statistically significant, with the exception of 4-authority vs 6-authority Less. As can be seen, fewer authorities leads to more chaotic evacuations as well. Both of these results are in line with expectation.

Next, as per security officials' interest, we examined the impact of having more authority figures to aid in recommending how many are needed to safely evacuate this space. Figure 8 shows the number of collisions over the course of the evacuation (in thousands), with the number of authorities listed on the x-axis. T-Tests revealed that settings of more than 8 authority figures did not produce statistically significantly different results from the 8-authority case. This result implies that for this particular space, using more than 8 authorities would not produce better results.

We also ran tests with an alternate patrolling strategy. The default strategy is to proceed to a randomly chosen 'patrol point', the list of which is predefined to be the corners of each area in the scenario. The alternate strategy we tested was to have authority figures patrol the perimeters of the waiting areas and hallways. Results pertaining to the number of collisions were not statistically significantly different, implying no benefit to either strategy in terms of calming the population. However, further analysis revealed another

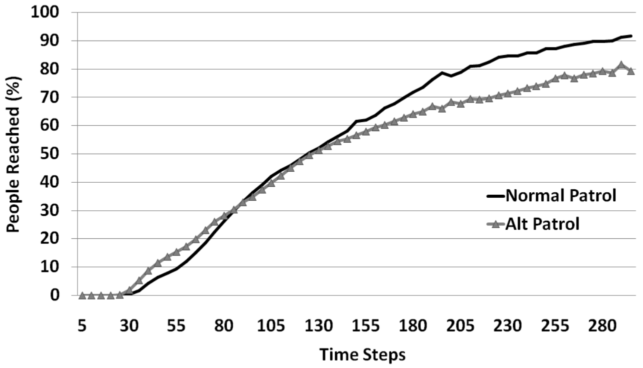

Figure 9: Effect of alternate patrol

trend.

Specifically, we looked at what percentage of the population would be reached by patrolling authorities on average within the first 300 time steps of the simulation. Figure 9 shows the percentage of people that were reached by authorities within 300 time steps. We show only the case of 6 authority figures, but all like comparisons showed the same results (although varying in degree of the difference). Namely, the alternate strategy lines were always steeper at the beginning of the evacuation, but flattened out, implying that initially the alternate strategy was superior, but as fewer and fewer people remained, the point-to-point strategy was superior. Patrolling the edge of the room is effective to reach agents on the outskirts and more evenly distributes authority figures, but due to the large size of the waiting areas, crossing the room to reach different corners ultimately covers more ground. These results imply that a coordinated authority policy that intelligently covers the ground would be superior to both.

6. CONCLUSION

In this paper, we describe ESCAPES, a multiagent evacuation simulation tool that incorporates four key features: (i) different agent types; (ii) emotional interactions; (iii) informational interactions; (iv) behavioral interactions. These features are grounded in social psychology and evacuation research and tailored towards the needs of an airport security official (as well as other situations with similar features such as a mall, where homogenous agents are a poor approximation). Furthermore, as shown in Table 1, the features result in a breadth of emergent behaviors that have been observed in the literature, implying increased fidelity of our simulation as a result of their inclusion. We also show results based on a model of Los Angeles International Airport's Tom Bradley International Terminal with concrete recommendations that can be produced with our simulation.

In discussions with security officials affiliated with LAX, ESCAPES received high praise. Officials mentioned that the 3D visualization we provide is far superior for training and planning to other systems they have tried in the past. The inclusion of families and authorities as well as realistic knowledge spread about event and exits were specifically mentioned by them as being important and something they have not yet seen. The ability to adjust the number of families, pedestrians, and authorities in each zone was crucial. Overall, ESCAPES was very well received by security officials affiliated with LAX.

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