Computational Emotions Encourage Collective Behavior in Population Dynamics

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We evaluate how a computational model of emotions may enable collective behavior in a predator-prey system. Our cellular automata model combines emotion-based decision rules with simple communication. Although there are a number of human psychological theories of emotion, it is generally agreed that emotions increase our ability to interact with our environment. Human emotions may have initially evolved for survival, showing many commonalities with predator-prey scenarios. Additionally, groups of prey will exchange information about their surroundings to increase their survival. We therefore define emotions for predators and prey based on these theories of emotions and Ekman's basic emotions. Our system describes the interactions of foxes that feed on rabbits that feed on carrots. Emotions are used by foxes and rabbits and encode data pertaining to survival. We examine variations of the communication, and to what extent an individual's decisions should be based on the communicated emotion versus the personal emotion. We find that the emotion rules and communication allow each population to cooperate and improve their population's fitness.

1   Introduction

Collective behavior can refer to both human and animal tendencies to influence each other's behavior. In this paper we are most interested in collective animal behavior that leads to improved species survival within a predator-prey system. A major topic of population dynamics, the study of the development of either a single or multiple interacting species, is the cycling of predator and prey populations. Predator-prey dynamics relate to a wide variety of ecological situations, from microbial phagocytosis to lions and gazelles. Most often predator-prey systems are built to describe animal species, with at least one species as prey and one as predator; however, they are not limited to describing only two species. The Lotka-Volterra [14] equations are based on the classic logistic equation, and commonly used to model this type of interaction. However, it has been argued that these equations are not sufficient for modeling natural phenomena[13].

Cellular Automata (CA) offer a popular mechanism to analyze population dynamics as they directly represent spatial interactions between entities [12]. CA allow the creation of rules for determining how an entity will interact with its neighbors. CA can give rise to complex dynamics via simple rules, which enhances its desirability for modeling complex phenomena such as collective behavior, assuming that the appropriate simple rules can be designed or learned. In population dynamics CA models, entities explicitly exist on a grid and interact with specific neighbors. The system not only knows how many of each species is in the system, but to what extent they are mixed.

Our predator-prey model is an analysis of foxes that feed on rabbits that feed on carrots, although the name of each species is irrelevant. For collective behavior to arise information is shared between conspecifics and individual decisions are made on that information. The information shared is in the form of emotions, and both rabbits and foxes make decisions with their emotions and the shared emotions taken into account. Emotions are affected by environmental events, and thus represent a high level of information about the environment. Although emotions may initially seem like an odd form of information to share, the development of emotions in higher animals has been conjectured to originate for purposes of survival in basic scenarios such as predator-prey [2, 15], and thus emotionally-inspired rules are a natural extension.

Similarly, in the last few years it has been suggested that emotions constitute an important part of adaptive decision making systems, contradicting the older view that emotions typically interfere with decision making [6, 22]. Case studies reported that people who suffered injury to or loss of areas of the brain related to emotion also experienced impaired decision making [1]. Instead of showing the benefit of decision making to only an individual when emotions are involved as is done in these studies, we examine the benefit of emotions for the group.

Thus, we choose to include the six basic universal emotions as defined by Ekman [9] for our rabbits and foxes: happiness, sadness, fear, anger, disgust, and surprise. Emotions occur in response to specific world events, such as the happiness of food consumption and the fear of predator encroachment. Additionally, we enable conspecific communication of emotions to aid in coordination and co-

operation. The emotional state of a member of a species can be communicated to a member of the same species and thus affect their emotional state.

We consider this approach to emotional communication as an efficient way of transferring information that is crucial for the survival of the group, and analyze two different techniques for sharing emotion: direct sharing from neighbors, and stigmergic sharing [16]. Our goal is to determine which modeling approaching leads to the best collaboration within a species. Although our individuals are inherently selfish in that they make the best decision for themselves, our results show that communication of emotion can increase collective behavior for both predator and prey.

2   Previous Work

Cellular automata are often modified to simulate new topics, with one of the first being von Neumann's description of self-replicating automata [24], which has been built upon extensively. One such extension is the work of Petraglio toward creating a cellular automata capable of performing arithmetic operations by using self-replication of the cells [18].

Predator-prey models in particular often depend on spatial interaction and thus can benefit from CA modeling. Multiple interacting species move around the grid, with predator chasing prey. In some models, movement is purely defined by the birth of new entities into neighboring cells [7, 10], whereas other models allow individuals to actively move around the grid [8, 11]. We will allow two of our species to actively move (rabbits and foxes), and one to only move by reproduction (carrots).

For predator-prey dynamics in a CA it is useful to analyze the patterns created in the system. This can include how the number of predators and prey fluctuate in the system over time with differing parameters, as well as how mixed they are spatially [7, 11]. Results from [7] indicate that a combination of Lotka-Volterra [14], an individual's ability to change, and the spatial structure of the CA give rise to both predators and prey self-organizing into self-sustaining patterns. It has also been proposed that taking the environment into account significantly affects results, potentially making them more realistic as living creatures naturally have outside influences other than a predator or prey [10].

Although there are a number of human psychological theories of emotion [9, 19, 20], it is generally agreed that emotions serve the purpose of increasing our ability to interact with our environment in a successful manner. We propose that emotions could thus be used to increase collective behavior in a population dyanmics model. Rolls has argued that human emotions have ten functions, including reflexive behaviors and motivation [20]. These functions are advantageous for predators and prey as well, causing them to react quickly when near the other. It has been suggested that human emotions were initially evolved due to the need to survive, showing many commonalities with reactions of prey and predator to each other [19, 15]. Although there have been arguments that any defensive action in a prey represents emotions, more recently that view has been

modulated to instead argue that although this may not always be the case, it is still likely that initial reactions to threat in animals can precede emotions [2].

Collective animal behavior is often studied from a few different perspectives: examining biological causes of collective behavior in animals [16], examining how to build models to capture collective behavior [4], and being inspired by collective behavior [3]. Often these overlap, as more recent interdisciplinary efforts use modeling to help decipher the biological phenomena and create a better understanding of what underlying mechanisms can result in various forms of collective behavior.

The goal of our study is to introduce emotions to a species by including rules on how each individual gains and updates emotions, how the emotions of the individuals are shared with other conspecifics, and how each member changes its behavior locally based on its emotional state. Groups of prey in real situations will exchange information about their surroundings, increasing their likelihood of survival [23]. In the proposed model, the communicated emotions will include hints about a variety of survival conditions such as satisfaction (from food), fear (from predator), and disgust (from food poisoning). These emotions will result in behavior directing the individual to move in the best direction for survival. We hypothesize that outcome will be a coordinated group of individuals.

3 Our Model

We use a four-species CA based model to examine predator-prey dynamics in an environment that represents disease and where emotions are developed individually and communicated to neighboring conspecifics. Each point in the model may hold a single entity from any species at any given point in time. For ease of description we label our primary species as rabbits, foxes, and carrots, each of which are able to reproduce, move, and die. Empty spaces (the fourth species, vacancies, as described in the literature) represent an area where any of the other species may reproduce or move. Our grid structure is defined as a torus, and thus there are no corners requiring special treatment. Each individual's next step is determined based on probabilities and their neighbors within the Moore neighborhood (8 neighbors).

At the start of the first simulation, foxes, rabbits, and carrots are placed randomly such that no individuals overlap. Carrots are food for rabbits, rabbits are food for foxes, and foxes are at the top of the food chain. For simplicity all reproduction is asexual. Some aspects of the model results may be slightly less realistic as a result, but as the goal is to examine the use of a modeling technique instead of directly modeling a specific environment, our hypotheses can be equally tested in either case. A predator eats a prey when it moves to the prey's position. Once all of a species have been eaten, no more of that species can come into being in the system. However, as long as there is still at least one of a species alive it is possible for it to reproduce to create a new one.

Rabbits and foxes can exist either with or without emotions. Carrots are not affected by emotions. We will first describe the model without emotions,

and then describe how emotions are generated and how they modify individual behaviors within the model. In our results we will compare the scenario of no emotion with the scenario of using emotion.

3.1 Probabilistic and Neighbor-based Rules

At each time step, each cell occupied by a carrot will update following these rules:

- Reproduction: If it is at maturity age it produces a new carrot into a vacant adjacent square, if one exists. Age is reset to zero.

- Disease: When a new carrot is produced it has a 0.1 probability of being diseased. If the parent is diseased, the probability doubles.

- End of disease: Disease lasts for a minimum of 2 timesteps. After that minimum time has elapsed, there is a fixed probability $Cure$ of disease being cured each timestep.

Rabbits and foxes follow slightly more advanced rules at each time step:

- Movement: Movement occurs by computing a local gradient of preference for the surrounding cells as seen in Eq 1. Species can only move to a cell containing another individual if that individual is their food source.

$$g_{d,sp}(t, x, y) = food_{sp}(t, x_d, y_d) \tag{1}$$

  where d in $D = \{NW, N, NE, W, E, SW, S, SE\}$, t is the current time, $g_{d,sp}(t, x, y)$ represents the preference for each direction d at time t for an individual at location (x,y), sp $\in$ {rabbits, foxes}, and $food_{sp}(t, x_d, y_d)$ returns the existence of prey for a given species, sp, at locations in direction d from position (x,y) at time t calculated on that gridpoint and its two neighbors. These preferences are converted to normalized probabilities that bias the individual's otherwise random movements.

- Movement rate: When diseased it will have a decreased probability of movement each timestep ($DiseaseMove$).

- Hunger: Hunger increases by 1 each timestep it doesn't eat, or by 2 if it is diseased. Hunger is decreased to zero when it eats.

- Disease: If a predator eats a diseased prey, the predator becomes diseased as well. Disease lasts for a minimum of 2 timesteps. After that time elapses there is a probability $Cure$ of disease being cured each timestep.

- Reproduction: If it is of maturity age there is a fixed probability Rep of a new rabbit/fox being created in a vacant adjacent square, if one exists. The individual's age will continue to increase until it reproduces, and then it will be reset to zero.

After all entities have followed these steps, each will increase their age by 1.

Emotion	$X_{e,sp}$ (t,x,y)
Happiness	1 if ate prey, 0 otherwise
Sadness	t [timestep of last reproduction]
Anger	exp^{hunger}
Fear (fox)	Anger of neighboring foxes
Fear (rabbit)	Number of neighboring cells with foxes
Disgust	1 if ate diseased prey, 0 otherwise
Surprise	$\sum_e \frac{E_e(t,x,y)-E_e(t-1,x,y)}{5}$, where e does not include surprise

Table 1: Experience values affecting each emotion. For each emotion the corresponding value of the experience variable is listed.

3.2   Individual Emotions

Rabbits and foxes can use emotion in the model, but carrots do not. Emotions are calculated at the end of the sequence described in the previous subsection, and are used by rabbits and foxes when determining the next movement direction as well as their probability of reproducing. They are based on Ekman's original six basic emotions (fear, anger, sadness, happiness, disgust, surprise; [9]). Each individual maintains values of their own emotions. Emotions are independent for both rabbits and foxes, and each emotion is affected by different experiences related to neighbors, hunger, reproduction, and disease. The numerical values used to represent these experiences when calculating emotions can be seen in Table 1. Individuals also communicate their emotion, which can influence the emotions of other nearby individuals from their own species. Communicated emotions of one species cannot be seen or interpreted by the other species.

An individual's emotions are based on experiences, as well as their previous emotion and the emotions being communicated nearby. They are computed at each time step as seen in Eq. 2. The previous emotion and communicated emotion are both discounted, to prevent them from overpowering newer experiences or causing monotonically increasing emotions over time.

$$
\begin{aligned}
E_{e,sp}(t+1,x,y) &= (1-c_{m,sp})(X_{c,sp}(t,x,y)+c_{c,sp}*CE_{e,sp}(t,x,y)) \\
&+ c_{m,sp}*E_{e,sp}(t,x,y) \quad\quad (2)
\end{aligned}
$$

where e $\in$ {fear, anger, sadness, happiness, disgust, surprise}, sp $\in$ {rabbits, foxes}, $X_{e,sp}(t,x,y)$ is the unique experience of each emotion for each species (Tbl. 1), $c_{m,sp}$ is the memory discounting coefficient that determines what percent of the new emotion is based on new versus old emotional information and is calculated as in Eq. 3, $c_{c,sp}$ is the discounting coefficient for communicated emotion, and $CE_{e,sp}(t,x,y)$ is the communicated emotion at position (x,y) at time t as shown in Eq. 4 and Eq. 5. The coefficient $c_{m,sp}$ is bounded to [0.1,0.5] and $c_{c,sp}$ is bounded to [0,1).

$$
c_{m,sp} = 0.1 + 0.4 * \frac{abs(E_{surprise,sp}(t,x,y) - E_{surprise,sp}(t-1,x,y))}{E_{surprise,sp}(t,x,y) - E_{surprise,sp}(t-1,x,y)} \quad\quad (3)
$$

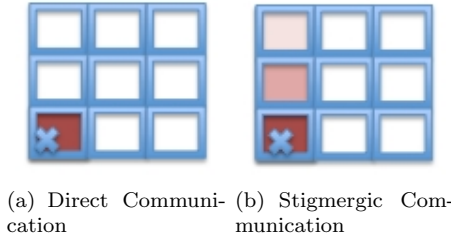(a) Direct Communi-
cation

(b) Stigmergic Com-
munication

Figure 1: The two communication styles. The 'x' represents where an entity currently exists, and the colored background represents the currently shared emotion at that cell (darkest is strongest). Both images represent the state of the shared emotion from that entity after three timesteps.

Emotions are computed for each individual. The calculation of communicated emotion is dependent on which communication paradigm is in use.

3.3   Emotion Communication - Direct

In this case, only emotions from the immediate neighborhood from the previous time step are used in the decision (Figure 1(a)). Additionally, emotions are only read from the map if a conspecific existed at that point; i.e., only emotion shared from events in the previous timestep are included. An individual will overwrite old emotions at their location between timesteps. When an individual is determining their own emotions for timestep (t+1), they will calculate what emotions are being shared through the environment via Eq. 4 from timestep t.

$$CE_{e,sp}(t, x, y) = \sum_{d \in D} S_{sp}(t, x_d, y_d) * E_{e,sp}(t, x_d, y_d) \tag{4}$$

where e $\in$ {fear, anger, sadness, happiness, disgust, surprise}, sp $\in$ {rabbits, foxes}, D represents all directions, $S_{sp}(t, xd, yd)$ returns 0 or 1 denoting the existence of species sp in direction d from position (x,y) at time t, and emotion $E_{e,sp}(t, x_d, y_d)$ is the amount of emotion in direction d from position (x,y) at time t. After emotions and communicated emotions have been calculated for all entities in the system, all emotions (both internal and communicated) are decayed linearly by a small value denoted in Tbl. 2. This version of communication is identical to the version analyzed in our previous study [17].

3.4   Emotion Communication - Stigmergic

With stigmergic communication, the shared emotions will remain at the cell over time and will decay with each timestep (Figure 1(b)). When an entity moves to that cell and leaves its own emotional mark, the newly shared emotions will be combined with the previously shared emotion. This thus affects the calculation of what shared emotions an individual's emotion is affected by, as seen in Eq. 5.

$$CE_{e,sp}(t, x, y) = \sum_{d \in D} E_{e,sp}(t, x_d, y_d) \tag{5}$$

where e ∈ {fear, anger, sadness, happiness, disgust, surprise}, sp ∈ {rabbits, foxes}, D represents all directions, and emotion $E_{e,sp}(t, x_d, y_d)$ is the amount of emotion in direction d from position (x,y) at time t.

After emotions and communicated emotions have been calculated for all entities in the system, all emotions are decayed. Although the individual emotion is still decays linearly as with the Immediate Neighbor communication, we test two different form of decay for the communicated emotion: linear and geometric (values in Tbl. 2). This variety of decay examines whether the rate of decay affects the emotional decisions of the predator or prey.

3.5   Rules Enhanced by Emotions

Rabbits and foxes with emotions have altered reproduction rates, and movement direction preferences from their unemotional counterparts. Other aspects are calculated the same as shown in the Probabilistic and Neighbor-based Rules section.

Reproduction Rates: Rabbit and fox reproduction rates are altered positively by happiness, and negatively by disgust and anger. Additionally, rabbits will not reproduce at all while their fear is above a threshold. The calculation of reproduction rate can be seen in Eq. 6.

$$
\begin{aligned}
R(t) \quad = \quad & Rep * (1 - Rep) * (E_{happy}(t, x, y) \\
- \quad & Rat * E_{disgust}(t, x, y) - (1 - Rat) * E_{anger}(t, x, y))
\end{aligned} \tag{6}
$$

where R(t) is the probability of reproducing at time t, Rep is the initial probability of reproducing after the maturity age has been reached, Rat is the ratio of how much disgust versus anger decreases reproduction, and $E_{happy}(t, x, y)$, $E_{disgust}(t, x, y)$, and $E_{anger}(t, x, y)$ represent current emotional values.

Movement Preference: The local preference gradient for movement considers emotions, where an individual will move toward the highest positive value $g_{d,sp}(t, x, y)$. This differential is taken to be the difference between the emotion in a given direction and the current emotion of the individual, as seen in Eq. 7.

$$
\begin{aligned}
g_{d,sp}(t, x, y) \quad = \quad & food_{sp}(t, x_d, y_d) \\
+ \quad & \sum_{e} valence_e * (E_{e,sp}(t, x_d, y_d) - E_{e,sp}(t, x, y))
\end{aligned} \tag{7}
$$

where (x,y) represents the individual's current location, (xd,yd) represents locations in direction d, e is taken over all emotions except surprise, and $valence_e$ is -1 for a negative emotion e (fear, anger, sadness, disgust) and 1 for a positive emotion e (happiness).

Emotions are used to encode and communicate various features of the environment to modulate the behavior of individuals. The components of the environment incorporated into emotions are intuitively useful for survival, which suggests that emotions should modify the behavior of individuals in a way that is beneficial for their species.

	Carrot	Rabbit	Fox
Rep	n/a	0.75	0.75
Maturity Age	2	6	7
Cure	0.8	0.8	0.8
DiseaseMove	n/a	0.8	0.8
Starvation	n/a	2	6
Rat	n/a	0.4	0.4
Fear threshold	n/a	n/a	0.5

Table 2: Simulation parameters.

4   Results

4.1   Experimental Design

The simulation is run on a grid world of size 50 x 50. Each point on the grid interacts with its Moore neighborhood of radius 1. Simulations are run for a total of 2000 time steps with an initial random placement of individuals on the grid. Each of the twenty initial placements are tested on the four emotion scenarios: no emotions, only foxes using emotions, only rabbits using emotions, and both species using emotions.

We test three communication coefficients ($c_{c,sp}$:0.1,0.5,0.9) for each communication paradigm. For the stigmergic communication we test two types of decay, each with two emotion decay rates: linear (0.1,0.5) and geometric (0.5,0.9). Initial population sizes for foxes, rabbits, and carrots were 240, 500, and 1500. Initial parameter searches were done on both population parameters and emotion parameters for all populations to determine which parameters to investigate further (Table 2). Experiments were run to determine how beneficial the use of emotions was for each population (rabbits and foxes). We compare how the populations and individual emotions differ in terms of different communication paradigms (direct vs stigmergic), the amount of information used from the environment versus one's own information (communication coefficient), and how long the system and individual's memory of an emotion remains (decay rate).

4.2   Effect on Emotion

All rabbit emotions except for fear increase with an increase in the communication coefficient (Figure 3). Thus, there is enough emotion sharing (except for fear) on the grid that it increases the emotion when the environment has a strong effect on an individual. However, only a fox's fear is significantly increased as the communication increases; all other emotions are essentially constant (Figure 4). This suggests that there are too few foxes for effective communication, which is supported by the constant level of emotion when foxes use direct communication.

All rabbit emotions except anger and sadness are stronger when both species use emotion instead of only rabbits using emotion. The increase of fear in rabbits when foxes also use emotion is of particular interest, as it supports the idea that fox emotion improves their performance. Rabbit anger is increased when only rabbits use emotion, but rabbit sadness doesn't change. All independent fox
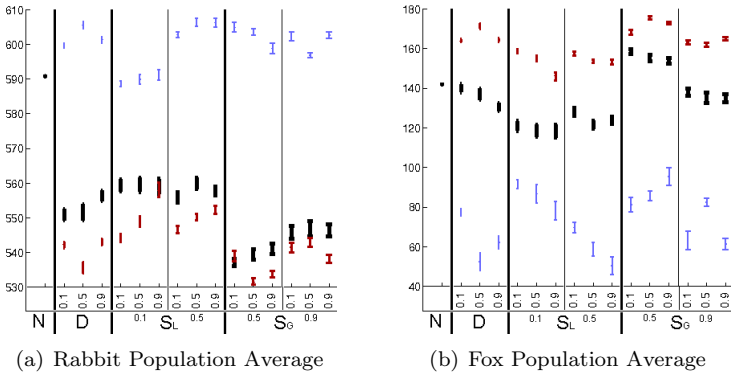
(a) Rabbit Population Average   (b) Fox Population Average

Figure 2: Average rabbit (a) and fox (b) populations for each parameter combination. The x-axis shows the communication coefficients (0.1,0.5,0.9) and decay values for each type of communication (N: no communication; D: direct; S: stigmergic (L=linear, G=geometric)). Black (darkest) represents when both species use emotion, Red (second darkest) represents when only foxes use emotion, and Blue (lightest) represents when only rabbits use emotion.

emotions except fear are the same when either only foxes use emotion or both species use emotion.

For both species a higher geometric decay rate with stigmergic communication leads to more emotion than a lower geometric decay rate. A linear decay affects rabbit and fox emotion differently, however. For rabbits, stigmergic communication with a lower linear decay always leads to higher emotion than with a higher linear decay. For foxes, both linear decay rates lead to the same level of anger, disgust, and happiness. However, an increased linear decay rate leads to decreased sadness and increased fear for foxes.

Stigmergic communication with low linear decay leads to the highest levels of rabbit sadness and disgust. Rabbit fear is increased the most with either direct communication when both species use emotion, or with stigmergic low linear decay when only foxes use emotion. Linearly decayed stigmergic communication tends to lead toward higher fox anger, sadness, and fear than with a geometric decay; the opposite is true for disgust and happiness.

Direct communication leads to the highest levels of rabbit anger and happiness. Direct communication leads to lower fox anger and fear but higher sadness, disgust, and happiness than a linearly decayed stigmergic communication. Since anger and happiness are both related to hunger in inverse ways, it is not surprising that the fox emotion trends between the two emotions are essentially opposing each other.

All fox surprise trends essentially mimic fear. This leads to the suggestion that the primary factors of surprise, a composite emotion in our model, are fear and anger. As the emotional memory is inversely related to the amount of surprise experienced, fearful and angry foxes tend to base their memory and decisions upon more recent events. This is clearly a beneficial behavior that sug-
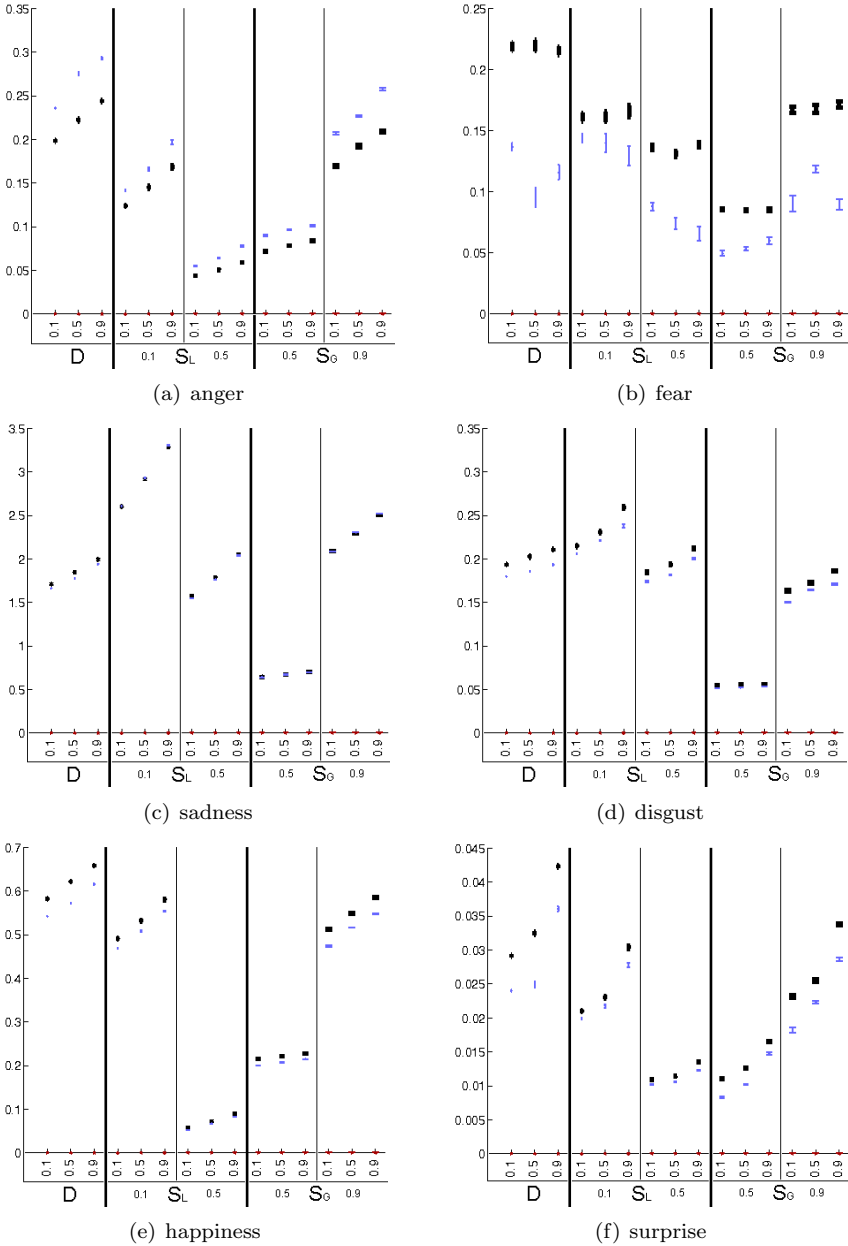
Figure 3: Average individual rabbit emotion for each parameter combination. The x-axis shows the communication coefficients (0.1,0.5,0.9) and decay values for each type of communication (N: no communication; D: direct; S: stigmergic (L=linear, G=geometric)). Black (darkest) represents when both species use emotion, Red (second darkest) represents when only foxes use emotion, and Blue (lightest) represents when only rabbits use emotion.
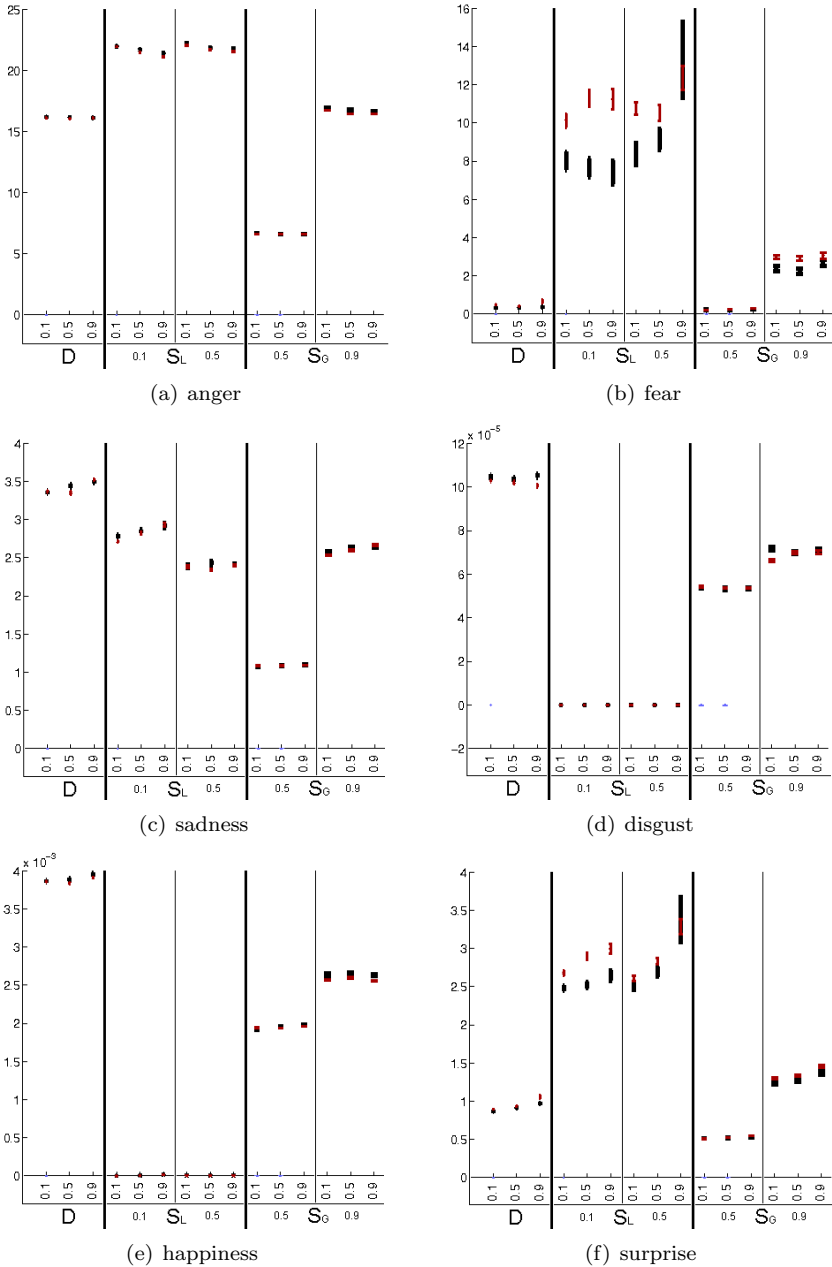
Figure 4: Average individual fox emotion for each parameter combination. The x-axis shows the communication coefficients (0.1,0.5,0.9) and decay values for each type of communication (N: no communication; D: direct; S: stigmergic (L=linear, G=geometric)). Black (darkest) represents when both species use emotion, Red (second darkest) represents when only foxes use emotion, and Blue (lightest) represents when only rabbits use emotion.

gests that foxes will adapt their behavior for the environment when experiencing these negative emotions.

4.3   Effect on Population

Population averages are consistently better for each species when they are the only species using emotion (Figure 2). Foxes additionally benefit from emotion when both species use emotion and either direct communication is used (with less than 90% of communication coming from the environment) or geometric decay is used with stigmergic communication.

We expect that high decay rates in stigmergic communication would lead to results that are almost indistinguishable from the direct communication case, as emotions would not be able to linger long enough to be significantly different from only counting the previous time step. This is generally true with respect to the range in which the populations fluctuate while varying the communication coefficient for both linear and geometric decay in both populations.

The rate of decay for stigmergic communication generally has no effect on the rabbit population, only causing a significant difference in population when only rabbits use emotion with a high linear decay. The fox population decreases as decay rate increases when only rabbits use emotion, and essentially does not change when only foxes use emotion. When both species use emotion, however, fox population stays relatively constant as linear decay increases but decreases as geometric decay increases. A potential cause of this can be seen in the surprise and fear of rabbits. The increase in surprise at a high geometric decay will cause rabbits to focus more on the present than the past, while a higher level of fear will cause rabbits to flee foxes.

As communication coefficients increase most rabbit emotions also increase. This is to be expected as the increased coefficients should lead to more emotion present in the system. For this reason the relatively constant level of emotion for fear in rabbits when both species have emotion regardless of the communication coefficient is interesting. This suggests that there is an optimal amount of information for a prey to convey about predators.

Linear decay in rabbits may have an upper limit on the amount of decay, which is not surprising. Geometric decay may also have an upper limit for rabbits, with respect to the communication coefficients. This could be the point at which there is effectively no more communication in the system, or perhaps just for some of the emotions.

Geometric decay has more complex effects on the fox population, while linear decay seems to generally be detrimental. More communication without geometric decay is generally bad for foxes.

5   Conclusions

We have analyzed the use of computational emotions toward increasing collaboration and collective behavior for both predators and prey in a Cellular

Automata predator-prey model. Both species were given emotions inspired by Ekman's six basic universal emotions and current research on how emotions affect animals in predator-prey scenarios. Two methods of communication were tested: direct communication, and stigmergic communication.

From the results we see that both species are benefited the most if they are the only species using emotion. However, we also see that the fox population benefits when both populations use emotion if information is stimergic communication is used with a low geometric decay. Thus, the predator is able to act collectively with a trail of information when it remains for a longer period of time.

All rabbit emotions except for fear are increased by an increase in the communication coefficient. However, only a fox's fear is significantly increased as the communication increases; all other emotions are essentially constant. Thus, rabbit emotions are more strongly affected by older information, whereas fox emotion is not.

Overall, communicated emotion can play a role in collective behavior for both predators and prey. Interestingly, the communication paradigm best for one species may be the worst for the other species. It will be interesting in the future to develop a system in which each species can evolve its communication strategies to see how the population dynamics and collective behavior are both affected by this additional dynamic.

Acknowledgments

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