Effects of Local Communication and Spatial Position in a Collective Decision-Making Model

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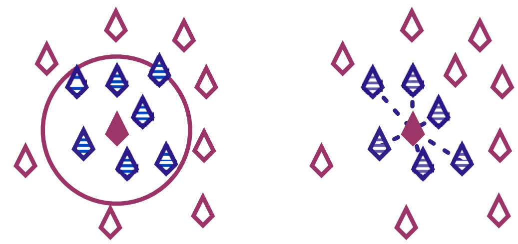
Abstract

Large-scale coordination in nature relies on the effective flow of information through a group. Understanding this flow is essential to implementing similar behaviors in artificial groups such as teams of robots, especially if communication is limited to an individual's closest neighbors as in nature. While observational studies of the spatial position of leaders, or initiators, of a decision in natural systems have been made, there has been a lack of studies specifically investigating the effects of position in more depth. In the work presented here, our simulations predict that centrally located individuals are more successful initiators than those on the periphery when communication is local. However, since there are many examples in natural systems of individuals located on the periphery successfully initiating, we incorporate the concept of temperament traits to modulate the decision-making process and improve initiation success in three different types of group behavior. Simulations predict that the addition of temperament traits do increase the probability of success for individuals on the periphery, although central individuals are still far more successful initiators. These results can be used to develop artificial systems in which tasks are completed by initiations from individuals on the periphery of the group.

Introduction

An individual's spatial position in a group has several implications on its overall fitness. For example, a position on the periphery of the group could offer more opportunities for foraging since new food patches are discovered there (Morrell and Romey, 2008). On the other hand, individuals on the periphery are more frequently the targets of predation, making central positions more preferred when predation is high (Morrell et al., 2010).

An individual's position relative to others is especially important when communication is limited and the group is large, as it determines with which neighbors the individual can interact and, ultimately, how information flows through the group. Figure 1 depicts the two more commonly proposed methods for determining an individual's interacting neighbors: metric distance and topological distance. Since these distance measures can produce significantly different communication networks, it is important to evaluate their effect along with an individual's position.



(a) Metric (b) Topological

Figure 1: Two different distance measures, metric and topological, proposed to determine the other individuals within a group with whom an individual interacts are shown.

In the work presented here, we use a biology-based collective decision-making model to explore how an individual's position within a local communication network affects its ability to effectively initiate consensus group decisions. We hypothesize that central individuals will be more successful initiators since there are more potential followers nearby. Simulations predict that these individuals do indeed have higher initiation success rates than individuals located at the periphery. However, this runs counter to many examples in natural systems of successful initiations originating at the periphery where new information is gained, such as fleeing from a predator. Our previous work demonstrated that the addition of a temperament trait can improve the initiation success of a group (Eskridge et al., 2015), but that work ignored the position of the individual in the communication network and relied on a single temperament trait. As a result, we further hypothesize that incorporating traits that modulate the decision-making for different group-level behaviors will increase the initiation success rate of individuals not centrally located. Further simulations predict that the addition of these traits do increase the success rate of peripheral individuals, but they are still less successful than those that are centrally located. These results can aid in the development of artificial systems which are given tasks that are frequently initiated by individuals on the periphery of the group, such as exploration or search and rescue.

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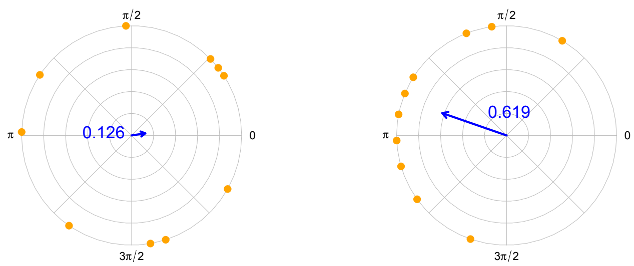

(a) Small MRV (b) Large MRV

Figure 2: An example of a small and large mean resultant vector (MRV) is shown. A small MRV indicates neighbors in all directions, while a large, MRV indicates neighbors in predominantly one direction.

Related Work

The role position plays in the collective decision-making process has been the focus of many studies, most of which emphasize collective movements. There are a variety of effects that position can have on an individual's ability to initiate and become a leader. Studies have found that individuals with a central position were able to recruit more followers and were therefore more successful at initiating movements (Sueur and Petit, 2008; Vital and Martins, 2013). One study on sheep found that initiation success depended on the spatial distribution of individuals in a group, with individuals on the periphery able to recruit more followers, especially if they had more neighbors (Ramseyer et al., 2009a). However, a similar study on cattle from the same authors was unable to conclude that spatial positions played any significant role in initiation success (Ramseyer et al., 2009b).

Implicit in each of these studies is the assumption that it is possible to determine which individuals are centrally located and which are in the periphery. There are a number of statistical measures, such as eigenvector centrality, that measure an individual's centrality in a network, like a social or communication network (Bonacich, 1987). However, these measures aren't practical when an individual must determine their own position relative to others in a group with limited knowledge. One measure that is practical, called the *mean resultant vector* (MRV), was found to be the best performing and most robust in a variety of situations when compared to three other measures (Christman and Lewis, 2005). It is computed by adding unit vectors from the individual to all its neighbors and then dividing the magnitude by the number of neighbors (Fisher, 1995). Small magnitudes indicate central individuals with neighbors that are distributed in all directions around the individual, and large magnitudes indicating peripheral individuals with neighbors predominantly in one direction (see Figure 2).

When restricted to local communication, individuals only interact with a subset of the group. These individuals with whom an individual interacts are often referred to as the individual's *nearest neighbors*. Biologists have long believed that individuals determine their nearest neighbors using a *metric distance*, since individuals have a limited sensory range (see Figure 1a) (Shang and Bouffanais, 2014a). Using a metric distance, all individuals within a specific distance d are considered nearest neighbors. While simple, there are potential problems with its use. Most importantly, it allows for the possibility of too many neighbors within the distance for the individual to effectively perceive.

Recently, researchers have determined that starlings in a flock use a *topological distance* for determining nearest neighbors. When a topological distance is used, the k closest individuals are considered nearest neighbors, regardless of their metric distance (see Figure 1b) (Ballerini et al., 2008), as there is a limit to the number of neighbors with whom an individual can interact (Shang and Bouffanais, 2014a). While a topological distance measure does address some problems of a metric distance, it allows for the perception of neighbors beyond a reasonable interaction distance. The argument for using a topological distance over a metric distance is that a topological distance allows for greater cohesion in sparse groups and is more stable (Shang and Bouffanais, 2014b). Since both measures are plausible, we evaluate both in the work presented here.

Another factor that can contribute to an individual's leadership success and spatial position relative to others in a group is *temperament* (Aplin et al., 2014). Temperament, also referred to as *animal personality*, is a set of repeatable differences in behavior across several traits (Réale et al., 2007; Dingemanse and Wolf, 2010). Although the most commonly studied trait lies along the bold/shy continuum (Frost et al., 2007; Harcourt et al., 2009b), recent work has identified as many as 14 different traits exhibited in a variety of behaviors in the primate literature alone (Freeman and Gosling, 2010). Earlier work in the area emphasized the fact that many traits were found to be correlated, but current work notes many situations in which traits commonly thought to be synonymous actually vary, even between populations of the same species (Bell, 2005; Massen et al., 2013; Yoshida et al., 2016). Thus, while some of these traits may be determined by the intrinsic state of the individual (e.g., nutritional needs due to size), other traits may be determined by the life history of the individual (Frost et al., 2007).

Methods

The simulations used for this work were built using a modified version of a collective decision-making model developed through observations of collective movement attempts in a group of white-faced Capuchin monkeys (Petit et al., 2009; Gautrais, 2010). The model was modified to accommodate local communication and to integrate the concept of temperament traits that modify the decision rates on an individual basis. These modifications were made to facilitate

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Parameter	Value
τ_o	1290
α_c	0.009
γ_c	2.0
ε_c	2.3
α_f	162.3
β_f	75.4

Table 1: Model parameters determined through direct observations of collective movement attempts in white-faced Capuchin monkeys.

the two sets of simulations. The first set of simulations used the model for a simple, large-scale decision, such as the entire group navigating to a distant location, to evaluate the effect of spatial position on the probability of successfully initiating. The second set of simulations used the model to evaluate the success probabilities of three different types of behaviors in which initiations from individuals from a range of spatial locations were likely.

Collective Decision-Making Model

Although modeled on collective movement attempts, this model does not consider actual movement. Rather, the focus of the model is on the decision-making process that precedes a movement. Examples of such situations are found in nature where individuals exhibit notifying behaviors indicating a preferred direction of movement during a predeparture period (Pyritz et al., 2011). The collective decision-making model consists of three probabilistic interaction rules. The equations corresponding to each rule produce a time at which each individual makes a decision. The individual with the earliest decision takes the desired action. The remaining individuals then recalculate the times for their decisions and the process repeats.

All individuals in the group can initiate a movement, which occur at a rate of $1/\tau_o$, with τ_o being a constant determined through observation (see Table 1). Since the model assumes global communication, once an individual initiates, all the other individuals in the group are assumed to have observed the initiation attempt and have the opportunity to follow the initiator. Individuals decide to follow the initiator at the rate $1/\tau_r$, where τ_r is calculated as follows:

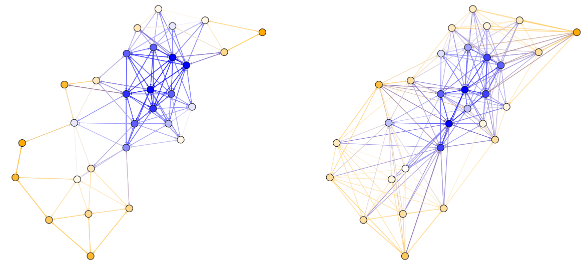
$$\tau_r = \alpha_f + \beta_f \frac{(N - r)}{r} \tag{1}$$

where α_f and β_f are constants (see Table 1), N is the group size, and r is the number of followers.

Not all initiation attempts are successful, as initiators often cancel and return to the group. However, as more individuals decide to follow the initiator, the rate at which initiators cancel is reduced as follows:

$$C_r = \frac{\alpha_c}{1 + (r/\gamma_c)^{\varepsilon_c}} \tag{2}$$

where α_c, γ_c, and ε_c are constants (see Table 1), and r is the number of followers.



(a) Metric (b) Topological

Figure 3: Networks resulting from the metric and topological distance measures are shown. Color denotes the number of neighbors that consider the individual a nearest neighbor, with blue indicating the most and orange the least.

Integrating Local Communication

Since the original model is based on observations of small groups, it assumes that individuals know the total number of individuals in the group, N, and that individuals know the total number of individuals following the initiator, r. To integrate local communication, these variables were altered to reflect the fact that individuals only interact with their nearest neighbors. N_i now denotes the number of nearest neighbors with whom individual i interacts, and r_i now denotes the number of nearest neighbors of individual i that have decided to follow. In each case, these numbers reflect the nearest neighbors of individual i, and not the number of individuals that consider individual i a nearest neighbor. While we have previously integrated local communication into this model (Eskridge, 2012), the modifications described here are more extensive and produce more accurate predictions. Since the type of distance measure can have significant effects on the determination of nearest neighbors, both metric and topological distances were evaluated (see Figure 3).

Integrating Temperament Traits

In previous work, we have shown that adding a temperament trait[1] results in increased group-level success of collective decisions (Eskridge et al., 2015). This is accomplished by modifying the rate equations to include a "k factor" which can result in either increased or decreased decision rates (see Figure 4)(Gautrais, 2010). Initiation attempts are calculated

[1]Previously, the *bold/shy* trait was referred to as simply "personality." Given the addition of other traits, the term "temperament traits" is now used, with the collection of traits referred to as an individual's "personality."

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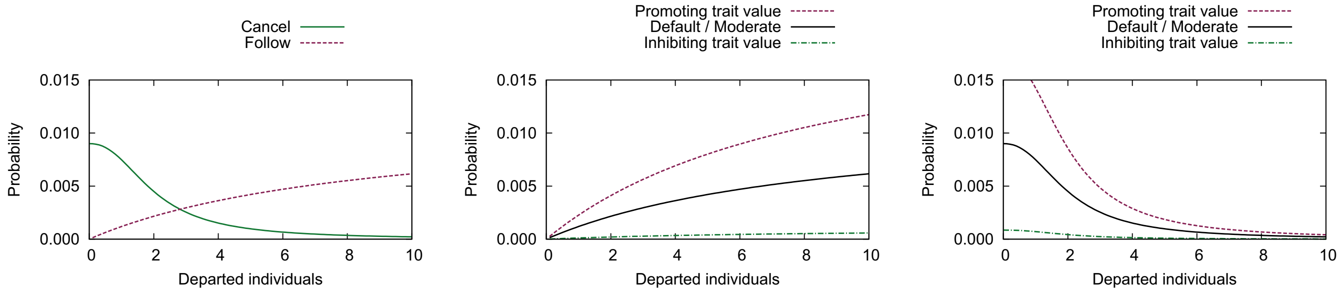
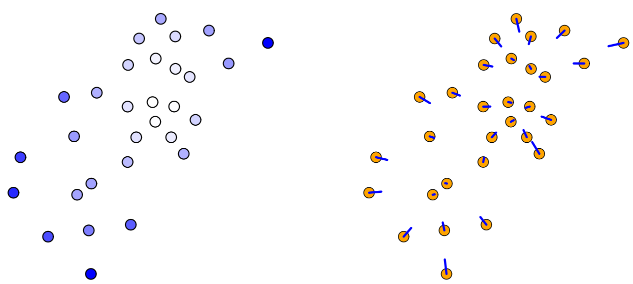


(a) Default rates (b) Effects on following rates (c) Effects on canceling rates

Figure 4: The default following and canceling rates are shown along with the effects of a temperament trait, both increasing and decreasing, on each.



(a) Mean distance (b) Mean resultant vectors

Figure 5: The mean distance to nearest neighbors for a representative spatial distribution of 30 individuals is shown in Figure 5a, with darker values denoting larger mean distances. The mean resultant vectors for the same spatial distribution is shown in Figure 5b.

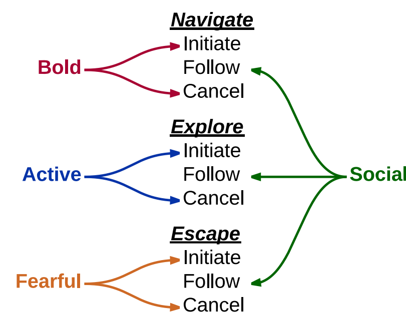


Figure 6: The three different group behaviors evaluated and the temperament traits that influence an individual's decisions in each. Higher trait values for *bold/shy*, *active/lazy* and *fearful/assertive* result in higher probabilities for initiation and lower probabilities of canceling. Higher *social* trait values result in higher probabilities of following an initiator.

at the constant rate of k/τ_o, and the following and canceling rate calculations are calculated as follows:

$$\tau_r = \frac{1}{k}\left(\alpha_f + \beta_f \frac{N_i - r_i}{r_i}\right) \quad (3)$$

$$C_r = k\left(\frac{\alpha_c}{1 + (r_i/\gamma_c)^{\varepsilon_c}}\right) \quad (4)$$

where the variables are defined as before. Since a single trait is only effective for a single task, this work introduces multiple traits for use with multiple tasks.

The specific traits investigated here were the *a*) *bold/shy* trait that is shaped by past experience and used for behaviors in a known risky environment; *b*) *social/solitary* trait which determines the extent that neighbor actions influence an individual; *c*) *active/lazy* trait that is shaped by the relative density of neighbors and used for behaviors in an unfamiliar environment; and *d*) *fearful/assertive* trait that is shaped by past exposure to predators and used for behaviors exhibited in response to perceived threats (Freeman and Gosling, 2010). Each trait had a value in the range [0.1:0.9] and was used to calculate the k factor as follows:

$$k = 2\left(1 + \mathrm{e}^{(0.5-t)\times 10}\right)^{-1} \quad (5)$$

where t is the temperament trait value.

The *bold/shy* trait is calculated using winner and loser effects from past initiation attempts for large-scale navigation of the entire group (Eskridge et al., 2015). A high *bold/shy* trait value results in a higher initiation rate and a lower canceling rate, while a low value results in a lower initiation rate and a higher canceling rate (Harcourt et al., 2009a). This temperament trait is used to modulate a standard navigation task in which the entire group must move to a known, and potentially risky, location. As in previous work, only a few, central individuals in a group were bold and the remainder were shy. The *social/solitary* trait is negatively correlated with the *bold/shy* trait such that an increase in one results in a decrease in the other. A high *social/solitary* trait value results in higher following rates in all behaviors, while a lower value results in lower following rates.

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The *active/lazy* trait is calculated using the relative density of an individual's neighbors as measured by the mean distance to its nearest neighbors (see Figure 5a). This trait affects the initiation and canceling rates of small-scale exploration decisions, such as splitting from the group to explore and forage for food, since a lower density affords a greater degree of freedom of movement. The distribution of these trait values was dependent on the relative positions of individuals in a particular simulation.

Finally, the *fearful/assertive* trait is calculated using an individual's position relative to the rest of the group as measured by the mean resultant vector (see Figure 5b). This trait affects the initiation and canceling rates of an escape behavior, such as fleeing from a predator, where initiations are made from the periphery of the group where predators are detected. Figure 6 illustrates the relationship between these temperament traits and the group-level behaviors. Note that since only the decision-making is modeled in these simulations, the only difference in these behaviors is the relative location of the most likely initiators.

Numerical Implementation

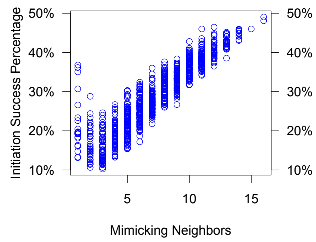
Numerical simulations of the collective movement model were implemented in Java using a customized version[2] of the original algorithm (Gautrais, 2010). Group sizes from 20 to 50 individuals were simulated. Group sizes any smaller would result in global communication and larger group sizes would show minimal differences in the results (Eskridge, 2012). For each group size used, simulations used 50 different spatial distributions of individuals, with both distance measures evaluated for each distribution. Each simulation constituted a single attempt at a collective movement and ended in success if the entire group participated in the movement, just as with the original model. In the first set of simulations, initiations were restricted such that each individual in the group had 2,000 simulations in which it was guaranteed to initiate in an effort to identify the effects of the individual's relative position in the group. In the second set of simulations, a group behavior was randomly chosen for each simulation and all individuals were given the opportunity to initiate with a total of $N \times 4,000$ simulations performed.

A wide range of values have been observed for the number of nearest neighbors when using a topological distance. Some work has observed values in the range of 6–8 (Ballerini et al., 2008), while other work has predicted 8–12 is optimal (Shang and Bouffanais, 2014b). In the simulations used here, a value of 10 was used to remain consistent with the original model, which was developed using observations of a group of 10 Capuchin monkeys.

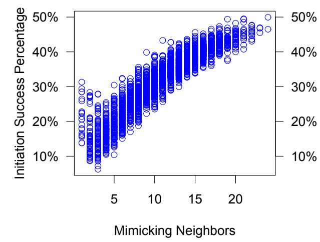
[2]Simulation source code and data analysis scripts are available for download from `https://github.com/snucsne/bio-inspired-leadership`

Type	$N = 20$	$N = 30$	$N = 40$	$N = 50$
Metric	0.916	0.918	0.925	0.924
Topological	0.934	0.942	0.949	0.950

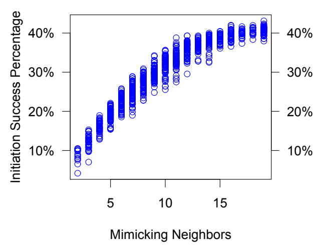
Table 2: Pearson's product moment correlations between the number of mimicking neighbors and initiation success.



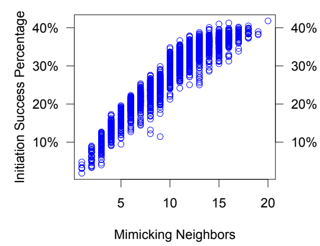
(a) Metric $N = 20$



(b) Metric $N = 50$



(c) Topological $N = 20$



(d) Topological $N = 50$

Figure 7: The number of mimicking neighbors for an initiator versus its initiation success probability is shown.

Results & Analysis

As described above, two sets of experiments were performed to evaluate the role of position in collective decision-making. In the first set, all individuals in the group were given the opportunity to initiate a collective decision for a large-scale navigation movement so as to analyze the effect of an individual's position on initiation success and failure. The second set of experiments simulated three different types of collective behaviors in which the initiator's position within the group affected its initiation and canceling rates.

Success Probability

An analysis of the results of the first set of simulations indicates that both the eigenvector centrality of an individual and the number of individuals that consider the initiator a nearest neighbor, referred to as *mimicking neighbors*, are effective predictors of initiation success. Both measures are positively correlated, but the mimicking neighbors measure is more relevant to the decision-making process at the level of the initiator. Table 2 shows the Pearson's product moment correlation between the number of mimicking neighbors for an initiator and its probability of initiation success for each group size. In each case, individuals with higher mimicking

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neighbor counts, meaning they had more potential followers and were more central to the communication network, were predicted to experience higher success. In fact, central individuals were predicted to have as high as 40% initiation success rate where individuals on the periphery were predicted to have as low as 10% initiation success rate. For comparison, the original model, without the restriction of local communication, had an initiation success rate with large groups of just under 50% (Eskridge et al., 2015). The topological distance measure resulted in stronger correlations than the metric distance measure, but the differences were minimal. Figure 7 plots the number of mimicking neighbors versus the initiation success for group sizes of $N = 20$ and $N = 50$.

A comparison of the metric and topological distance measures with respect to the number of mimicking neighbors shows that the topological distance measure resulted in statistically significantly more connections between individuals at lower group sizes of $N = 20$ and $N = 30$ (Student's t-Test $p << 0.001$), but the metric distance measure resulted in more for $N = 50$ (Student's t-Test $p << 0.001$).

Position-dependent Group Behaviors

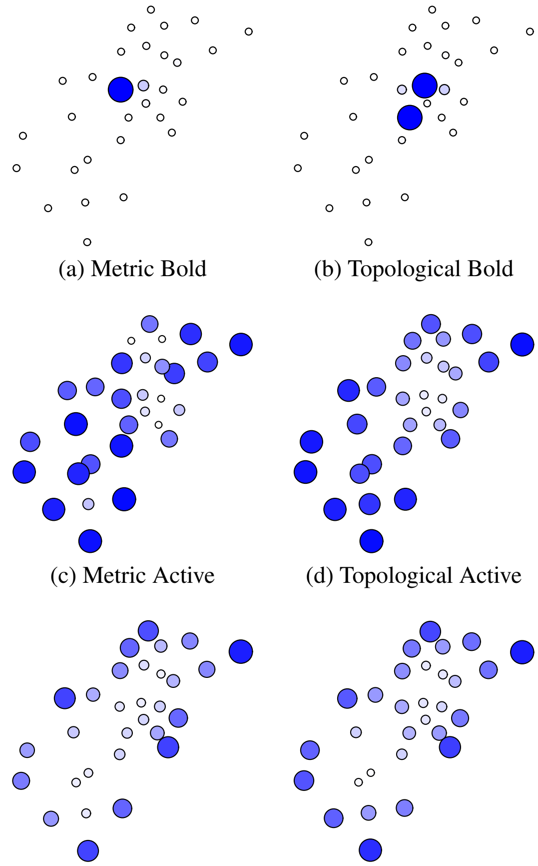
Table 3 shows the mean predicted success rate for each combination of behavior, distance measure, and group size for the second set of simulations. The navigate behavior had the highest mean predicted successful initiation rate, with some even reaching over 75%, which is consistent with previous work (Eskridge et al., 2015). In the other two behaviors, the success rate increases as the size of the group increases for the metric distance measure, but decreases for the topological distance measure. The majority of initiation attempts end with either the initiator canceling with no followers or all individuals in the group following the initiator. This is consistent with the original work describing the model (Gautrais, 2010) and indicate that once an initiator reached a threshold number of followers, they were likely to successfully recruit all the individuals in the group before canceling.

Figure 8 illustrates the distribution of temperament traits for a representative spatial distribution of individuals. A Pearson's product correlation test shows that the *active/lazy* and *fearful/assertive* traits were positively correlated when using the topological distance measure (0.782), but neither were correlated to the *bold/shy* trait. *Bold/shy* trait values exhibited a binary distribution of either high or low (see Figures 8a and 8b), while the other traits were distributed along the continuum. This binary distribution of the *bold/shy* trait is consistent with previous work (Eskridge et al., 2015) and is due to the use of winner and loser effects.

Discussion

The first set of simulations predict that individuals with a central location are far more likely to succeed in initiating than individuals located at the periphery, as anticipated. Our analysis indicates that the number of individuals which consider the initiator a nearest neighbor, referred to as the initiator's mimicking neighbors, plays a large role in determining success. Since the number of mimicking neighbors is higher for central positions, this leads to increased initiation success for individuals closer to the center of the group. Although we hypothesized that central individuals would have higher initiation success, it is particularly interesting that individuals at the periphery have such an extremely low predicted success rate, given that observations of natural systems indicate individuals at the periphery, where new information is gained, are frequently successful initiators.

The relationship between the group size and the distance measure with respect to the number of nearest neighbors is also interesting. In smaller group sizes with lower densities, the topological distance measure produces more connections in the communication network. However, for larger groups with increased densities, the metric distance measure produces more connections. This is not necessarily a gen-



(a) Metric Bold (b) Topological Bold (c) Metric Active (d) Topological Active (e) Metric Fearful (f) Topological Fearful

Figure 8: The distribution of each of the temperament traits for a representative spatial distribution of individuals using both metric and topological distance measures are shown. Higher trait values are represented by larger, bluer circles.

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Behavior	Distance	$N = 20$	$N = 30$	$N = 40$	$N = 50$
Navigate	Metric	0.727 ± 0.038	0.700 ± 0.056	0.673 ± 0.068	0.675 ± 0.073
	Topological	0.789 ± 0.053	0.750 ± 0.052	0.705 ± 0.058	0.662 ± 0.059
Explore	Metric	0.554 ± 0.087	0.593 ± 0.078	0.621 ± 0.057	0.630 ± 0.049
	Topological	0.529 ± 0.108	0.486 ± 0.075	0.476 ± 0.073	0.474 ± 0.068
Escape	Metric	0.513 ± 0.058	0.518 ± 0.054	0.532 ± 0.033	0.529 ± 0.036
	Topological	0.439 ± 0.049	0.396 ± 0.049	0.386 ± 0.036	0.378 ± 0.034

Table 3: The mean predicted success rate, including standard deviation, for each combination of behavior, distance measure, and group size are shown.

eral relationship as it depends on both the metric distance used and the relative spatial distribution of individuals, but it is something to consider when choosing a distance metric, especially if the spatial distribution changes over time. Although the differences between the mean success for the distance measures are small, the simulations predict that the metric distance results in higher minimum and maximum success percentages.

The second set of simulations predict that the addition of temperament traits can increase the initiation success for all individuals. The temperament traits modulate the decision-making process and can make initiation success more likely due to, among other things, reducing the likelihood of an initiator canceling. However, the relative spatial position of the individual, and its connectivity to the communication network, still played a significant role in the initiation success. The differences in the predicted success rate between the two distance measures are particularly interesting. For each behavior, larger group sizes result in greater success when the metric distance is used, but lower success when the topological distance is used.

Of the three behaviors, the navigation behavior, which used the *bold/shy* and *social/solitary* traits, is predicted to be more successful. This is most likely due to the binary nature of the *bold/shy* trait as shaped by winner and loser effects and its negative correlation with the *social/solitary* trait. As a result, individuals were either very bold and uninfluenced by the actions of others, or very shy and significantly influenced by the actions of others. While the other temperament traits could be transformed with a sigmoid function such as the one used for the *bold/shy* trait to promote such a binary distribution, it is unknown what the effects would be and if such a choice is merited.

The model and the simulation environment do have a number of limitations, which were primarily self-imposed to simplify the analysis. First is the limitation that the individuals do not move, which may limit the applicability of the predictions to static decision-making. This is primarily because the communication network will change as individuals change their relative positions by moving. Second, the stipulation that all individuals are required to participate in the behavior for the initiation to be called successful is too restrictive, despite this requirement being placed on the original observations of Capuchin monkeys. For example, the small-scale exploration behavior would usually only consist of a handful of individuals that split from the larger group. Also, the escape behavior is successful if the individual survives the perceived threat, regardless of the number of followers. Lastly, in more realistic situations, followers would be able to alter their previous decisions and choose to follow a new initiator, return to the original group, or initiate a decision themselves. If each of these limitations were lifted, the resulting behaviors and predictions could be quite different as conflicts can prevent consensus (Solum et al., 2014).

Conclusions and Future Work

The contributions of this work are as follows. Using our collective decision-making model, the first set of simulations predict individuals with central locations are more likely to succeed in recruiting followers than individuals at the periphery. Although this is consistent with observations of some natural systems, there are a number of situations in which these results are not consistent with observations. To explore such situations, a second set of simulations investigated three different behaviors, each of which normally are initiated from different locations in the group. These simulations predict that the addition of temperament traits can increase the probability of success for behaviors usually initiated by individuals that are not centrally located. Lastly, all the simulations predict that the choice of either a metric or topological distance measure also affect the initiation success, with the topological measure being more beneficial for low density groups and the metric measure being more beneficial for high density groups. These results can inform implementations of artificial systems which use collective decision-making models that seek to produce behaviors where initiations are made by non-central individuals.

As noted above, there are a number of limitations for the current simulations that could be removed. The most significant opportunity is to modify the simulations to include actual movement. Such simulations would provide an opportunity to study the changes in a group's communication network as different individuals with different positions ini-

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tiate and attempt to lead a movement. This would also provide a way to explore how the decision-making model can adapt to different types of decisions and movements, such as foraging or fleeing. We would also like to investigate a hybrid distance measure to address the weaknesses of the metric and topological distance measures.

Acknowledgments

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