A proposal to explore the dynamics of collective decision making using social foraging[1,2]

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Abstract

We recently developed a general mathematical framework to model the collective dynamics of a group of agents making decisions about a set of options. This theoretical approach allows us to extract the key parameters governing collective decision making, in particular, in terms of cooperation vs. competition among the agents and in terms of the resulting set of decisions (i.e., agreement, consensus, disagreement, polarization). Here, we suggest an interdisciplinary approach to collective decisions that uses a recently developed paradigm evaluating social foraging in human participants in combination with mathematical modeling. We plan to execute real-world experiments, where a group of simultaneous yet independent foragers must choose their search strategy in competitive, cooperative, or mixed scenarios. Such a feedback loop between theoretical predictions and experimental observations could lead to a quantitative theory of human behavior during real-world collective decision making and can potentially contribute novel paths to emerging areas such as computational psychology and psychopathology.

Key words: social foraging, collective decision-making, search strategies

Resumen

Recientemente, hemos desarrollado un marco matemático general para modelar la dinámica colectiva de un grupo de agentes que toman decisiones sobre un conjunto de opciones. Este enfoque teórico nos permite extraer los parámetros clave que rigen la toma de decisiones colectivas, en particular, en

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términos de cooperación vs competencia entre los agentes y en términos del conjunto de decisiones resultante (es decir, acuerdo, consenso, desacuerdo, polarización). En este trabajo sugerimos un enfoque interdisciplinario para las decisiones colectivas que utiliza un paradigma desarrollado recientemente que evalúa el forrajeo social en participantes humanos en combinación con modelos matemáticos. Con este marco teórico, planteamos las bases para ejecutar experimentos del mundo real, donde un grupo de recolectores simultáneos pero independientes deben elegir su estrategia de búsqueda en escenarios competitivos, cooperativos o mixtos. Tal ciclo de retroalimentación entre las predicciones teóricas y las observaciones experimentales podría conducir a una teoría cuantitativa del comportamiento humano durante la toma de decisiones colectiva en el mundo real y potencialmente aportar nuevos caminos a áreas emergentes como la psicología y la psicopatología computacional.

Palabras clave: forrajeo social, toma de decisión colectiva, estrategias de búsqueda

Collective decision making in experiments and in models

Collective decision making refers to the biological behavior in which a group of deciding agents jointly deliberate about a set of possible options such that the choice will both affect the individuals and the group as a whole. Examples of this behavior are found everywhere across evolutionary time and across phyla. Bacterial societies provide probably the most ancient and well-preserved collective decision-making behavior (Ross-Gillespie & Kümmerli, 2014). Depending on environmental conditions and using intercellular communication like quorum sensing, groups of bacteria can swarm, predate, develop, and differentiate in a fully coordinated fashion (Thiery & Kaimer, 2020; Guzmán-Herrera et al., 2020). Honeybee colonies take fully democratic decisions when they have to choose between candidate nest sites (Seeley & Buhrma, 2001). Schooling fish and flocking birds must constantly decide about the group movement direction in order not to break the flock and despite differences in desired movement direction at the individual level (Couzin et al., 2011; Leonard et al., 2012). Present and past human beings have always been faced with social choices: Where to forage? Where to settle a community? Who is the leader? Where to invest the capital? To leave the EU or not to leave the EU? Where to eat tonight? Who is the best candidate?

Collective decision making is not problem free. Not reaching a consensus usually comes with adaptive and evolutionary costs. However, how can diverging individuals' preferences lead to consensus decision making at the group level? How are personal and group benefits balanced? How does information exchange between the deciding agents affect collective decision making? How sensitive is democratic collective decision making to undemocratic attack like the use of bots and gerrymandering?

Although ultimately motivated by human collective decision making (Arrow, 1963), extensive effort has been put in trying to answer these questions in animal groups (Couzin, Krause, Franks, & Levin, 2005; King, Johnson, & Van Vugt 2009; Seeley, 2010). The obtained results can usually be extrapolated to the human level. For instance, a general conclusion is that the collective decision behavior cannot be explained by the prior preferences of the individuals alone. On the contrary, it is the interaction between prior preferences and inter-individual communication that determines the collective choice. A beautiful example is that of honeybee colonies, where a form of mutual dissuasion, mediated by a cross-inhibitory stop signal, allows the colony to make a democratic decision about a future nesting site. Mainly motivated by the extreme use of social media in opinion formation (Conover et al., 2011; Cohn, 2014; Bakshy, Messing, & Adamic, 2015; Lazer et al., 2018), recent experimental research in human collective decision making usually involves the use of computer games simulating a collective choice process (Kearns, Judd, Tan, & Wortman, 2009; Bond et al., 2012; Shirado & Christakis, 2017; Stewart et al., 2019). As opposed to experimental works in collective decision making in animal groups, experiments in human collective decision making tend to abstract the bodily and physical interaction level out of the decision process. A notable exception is King et al. (2010).

Collective decision making has been a fervid theoretical research field for a long time, in particular, for its mathematical modeling (DeGroot, 1974; Hegselmann & Krause, 2002; Galam, 2008). Recently, the theory of dynamical systems has contributed novel insights into the mechanisms of collective decision making via the powerful tools of bifurcation theory (Pais et al., 2013; Reina, Marshall, Trianni, & Bose, 2017; Gray, Franci, Srivastava, & Leonard, 2018). The basic idea is that the transition from indecision to decision can naturally be modeled as a bifurcation. Figure 1 illustrates this idea. The bifurcation diagram concisely summarizes the decision state of the decision-making network as relevant parameters change. For instance, the bifurcation parameter λ can model the strength of the agent interaction, whereas the unfolding parameter β can model the difference in option values. Continuous lines in the bifurcation diagram correspond to stable decision state, dashed lines to unstable decision states. When the agent interacts weakly (small λ), the network state is roughly midway between the two options. An undecided situation. As the interaction strength increases, the network converges toward a decision along different paths, depending on the difference in option values.

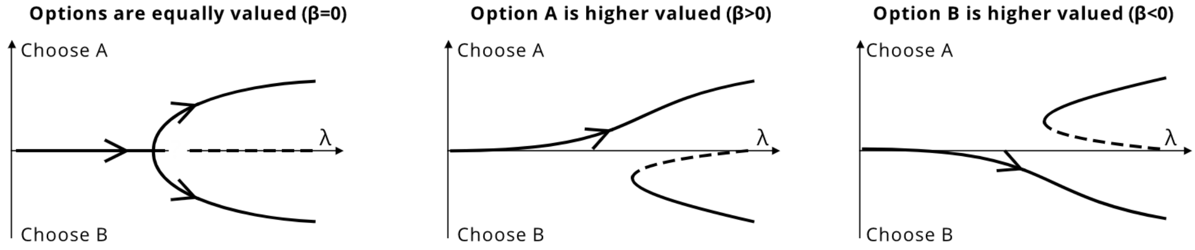

Figure 1. Decision making as a bifurcation phenomenon. See text for details.

When a large number of decision-making agents and a large number of choice options are considered, the bifurcation theory of collective decision making is largely unexplored. To explore it in a constructive way we made (Franci, Golubitsky, & Leonard, 2019) empirical assumptions about the properties of a democratic dynamical decision network. Namely, we assumed that agents are equal and that options are *a priori* equally valued. These assumptions can be translated into precise symmetry properties of the decision dynamics and the powerful tools of equivariant bifurcation theory apply (Golubitsky & Stewart, 2003). Leveraging these tools, we build a novel framework to understand collective decision making and make model-independent predictions about its dynamics. "Model independent" means here that our predictions are expected to be true in any system, mathematical or real, that approximately satisfies the symmetry assumptions we made. Our model independent predictions can be summarized as follows. i) Consensus and perfect disagreement (also termed *polarization* [Sunstein, 2002; Cohn, 2014]) are the only two generic decision states to which a dynamical decision network can converge from indecision. ii) In the perfect disagreement state, the appearance of extremist decision makers is generic. iii) The sensitive parameters underlying the transitions between the different decision states are fully characterized by the mathematical structure of the underlying symmetric bifurcation. To summarize we predict that the decision state of any dynamical decision network can be controlled by well determined parameter modulations to switch between different prototypical decisions (e.g. disagreement, extremism, consensus). Furthermore, a key parameter governing the decision state of a network is the balance between agent cooperation (agents follow other agents' opinions) and agent competition (agents reject other agents' opinions). Figure 2 illustrates this fact. When agents compete they tend to make opposite decisions.

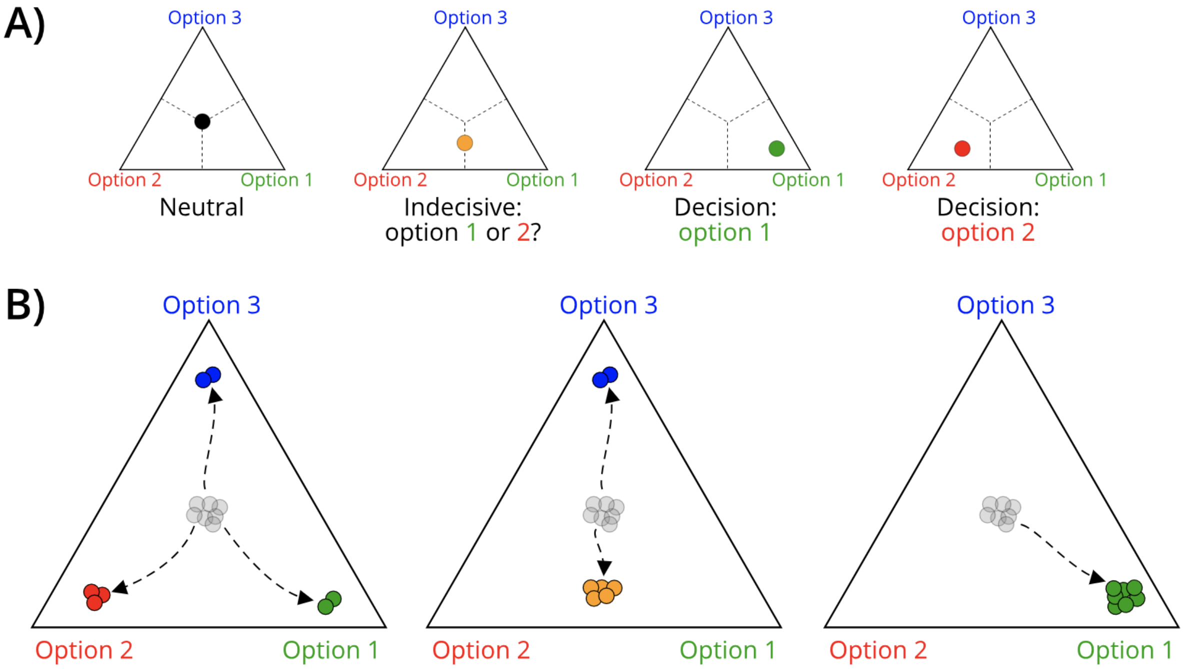

Figure 2. Possible decisions of a group of decision-making agents deciding over three options. **A)** Each agent state, represented by a colored circle, is projected onto a 2-simplex (a triangle), which represents the opinion state-space of an agent (right). The closer is an agent state to one of the vertices of the 2-simplex, the larger is the agent's preference toward the associated option. The closer is an agent state to the simplex center, the more undecided, or neutral, is the agent. An agent can also reject one of the options and be undecided between the two remaining options, in which case its state lies roughly midway between the vertices of the two preferred options. **B)** Possible decision behaviors. When agent compete (left and center), the group splits into clusters with opposite opinions about the available options. This splitting can be uniform (left), such that the opinion clusters have roughly the same size and the opinion strength is roughly homogenous across the agents, or of moderate/extremist type (center), such that a large group (the moderates) develop a weaker opinion than the small group (the extremists). When an agent cooperates (right), the group reaches consensus on one of the options.

We would like to end this section with a series of open questions and ideas for experimental and theoretical approaches to collective decision making:

- How does human collective decision-making work in real-world conditions, where energy costs, sensori-motor feedback, and face-to-face interactions are in play? In other words, what is the ecological validity of virtual collective decision-making experiments?
- What do real-world collective decision behaviors tell about the participants' psychosociology?

- Which mathematical modeling framework is suitable to quantify and analyze real-world human collective decision making?
- Can we use mathematical modeling to constructively identify experimental manipulations that steer such real-world collective decision behavior toward a desired outcome?

Social foraging as an experimental and theoretical paradigm

Foraging is a ubiquitous behavior, present in almost all mobile organisms (Bell, 2012). It can be defined as the movements made by an agent with the objective of obtaining resources i.e. food, mates, shelter, etc. Since foraging entails costs i.e. movement, manipulating prey, transport, etc., it is of critical importance to develop search mechanisms that are cost effective, that is, where benefits exceed the costs involved. In this sense, most models have revolved around "optimal" foraging decisions. Charnov's model (1976) proposes that when an organism is on a patch, i.e. a cluster of prey items, it should stay and collect prey until finding another item in that patch exceeds the cost of moving to a new patch. The simplest form of this model envisions a single forager searching for sessile prey that disappear once it is collected and involves a single decision: to stay or leave the patch. However, it is clear that things are more complex in the real world. One such complexity is brought on by the presence of another forager.

In a social foraging scenario, there are two or more agents in the same area simultaneously searching for the same items. Depending on the context, the addition of another agent could lead to two different situations, one involving cooperation, that is, all participants are competing against time and/or energy expenditure and must collect as many resources as possible through a joint effort, and one of competition, where searchers are not only fighting time and caloric expenditure but against each other and the winner is the one to take in more items (Clark & Mangel, 1986). An example of the former could be foraging as a group and sharing the benefits (Hill, 2002; Gurven, Hill, & Jakugi, 2004). The latter case could be exemplified by the type of conflict resulting over costly, scarce, or highly aggregated, well defined resources (Dyson-Hudson & Smith, 1978). It is important to remember that none of these situations are clear cut (Speth, 1990) – families feuds could influence competition among kin (Fry & Söderberg, 2013), and scarcity could also lead to cooperation and a stronger sensibility to inequality aversion (Kaplan, Schniter, Smith, & Wilson, 2012), bringing to light the vast complexity of such social scenarios. However, using experimental but biologically relevant simplified situations could be used to shed some light on individual decision making in such contexts (King et al. 2010; Jimenez, & Pietras, 2017).

Among the situations that have been used to explore foraging in an experimental context, we can find the Ball Search Field Task or BSFT (Rosetti, Pacheco-Cobos, Larralde, & Hudson, 2010; Rosetti, Pacheco-Cobos, & Hudson, 2016; Rosetti, Rodríguez, Pacheco-Cobos, & Hudson, 2016; Rosetti et al., 2016; Maya, Rosetti, Pacheco-Cobos, & Hudson, 2019; Rosetti, Ulloa, Palacios-Cruz, Hudson, & de la Peña, 2019). The BSFT intends to replicate the necessary conditions for searching behavior in a biologically relevant context and draws inspiration from the foraging for mushrooms (Pacheco-Cobos, Rosetti, Cuatianquiz, & Hudson, 2010). It aims to reach the middle point between experiments and ethnological work, avoiding computerized evaluation of searching behavior while conferring a certain degree of experimental control over the foraging situations. It involves testing subjects on large, open spaces so that the searching process involves a considerable spatial displacement. Subjects have to find easy-to-pick, sessile, non-regenerative items, e.g. golf-balls, on a setup previously arranged by the experimenter. Such arrangements can be modified so as to address different hypotheses: balls can be arranged in the form of grid, randomly or in patches (Figure 3A and 3B). In recent versions of the task, the potential location of items has been marked by the use of silicone cones (10 cm height) under which participants they may find a ball. These cones could be arranged into patches to make their presence distinct, while the information regarding patch density or distribution of items within the patch remains hidden to the participant. Other modifications involve simply changing the instructions, like priming of participants with information before they start their search (Maya et al. 2019). In order to address collaborative, social scenarios we can include more than one subject simultaneously (Figure 3C). In previous studies, Rosetti et al. (2016a, 2016b) tested the effect of age and sex composition by testing dyads on a searching task where the points collected by the pair would be summed up at the end of the task and then compared with scores of other teams. A competitive situation could be introduced by slightly changing such instructions so that the searcher with the most points wins.

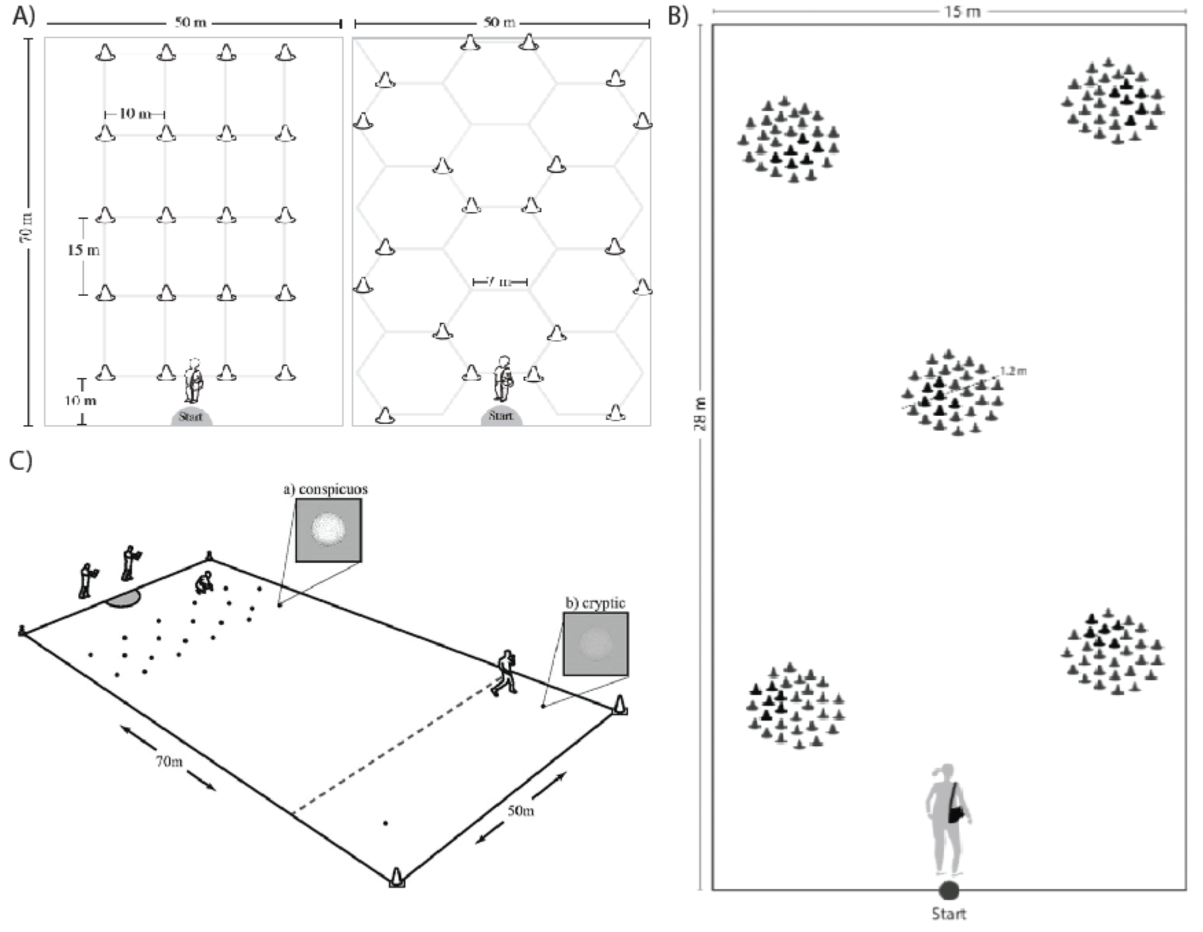

Figure 3. Examples of configurations of the BSFT. A) Cones arranged on a grid or as a pattern reminiscent of a honeycomb structure B) Cones arranged as patches, dark cones hide a ball underneath while grey cones are empty. C) An array for social foraging, where two sets of balls are placed on a large arena. White balls are numerous, located close to the start, are easy to see and worth a very few points; green balls are scarce and harder to see, located far from the starting point and worth several points.

To summarize, the BSFT could constitute a powerful paradigm to test how social decisions are made in real-world situations, that is, when time, energy, and gains (either monetary or symbolic) are involved. Here, we would like to propose experimental protocols with human participants that explicitly address collective decision-making in a foraging situation. The experimental protocols are inspired by and amenable to the equivariant bifurcation theoretical framework for collective decision making developed in (Franci et al., 2019). The designed task will allow us to study collective decisions under incomplete information using controlled experiments with human participants in a situation that is simple enough to analyze mathematically yet it retains salient features of real-world collective decisions.

A concrete proposal

The baseline experimental scenario we will set up is sketched in Figure 4. A certain number of patches (three in Figure 4), are symmetrically disposed in a large open area. Each patch consists of a large amount of opaque containers under which target items are hidden. Also, patches should be large so to deplete them quickly is not an option and players should make a considerable time investment if they wish to thoroughly search the patch. Participants will be instructed to begin their search at the center of the area where patches are located and to try and collect all items they can find, as per the typical instructions of a BSFT. They must follow ad-hoc rules that provide experimental means to control key psychosociological parameters, in particular, if and how players tend to cooperate or to compete. Concrete examples of these rules are provided below. The built-in symmetry of the experimental setup is important because it makes foraging option a priori equally valued. No a priori better option exists, so players must explore, communicate, and collectively decide where to forage. Symmetry is also important because it naturally allows to model and interpret experimental results via equivariant bifurcation theory, as discussed in the first section. The players collective dynamics will be video-recorded and post-analyzed to extract their positions and actions as the task evolves.

The basic rules at work during the BSFT and their psychosociological values are the following:

1. The task has to be completed in a short amount of time (variable and unknown to the players). This rule creates a time tension. Since the patches are far away from each other, the choice of leaving a patch in the search of a richer one is costly because of translation times.

2. Players in the same patch share their belongings when the BSFT ends. This rule creates a tension between personal and social benefits. Richer patches will attract more people but at the cost of sharing the collection with a larger number of players.

3. Depending on the outcome of their foraging, players might or not receive a monetary reward. This rule creates an actual will in the players to perform well and, possibly, earn money in return for their performance.

4. Participants openly discuss their strategies as there will be no limits on information flow. In other words, players decide if and how they will share their knowledge and ideas about patch quality and foraging strategies, for instance. This rule will allow spontaneously emerging verbal and social attitudes.

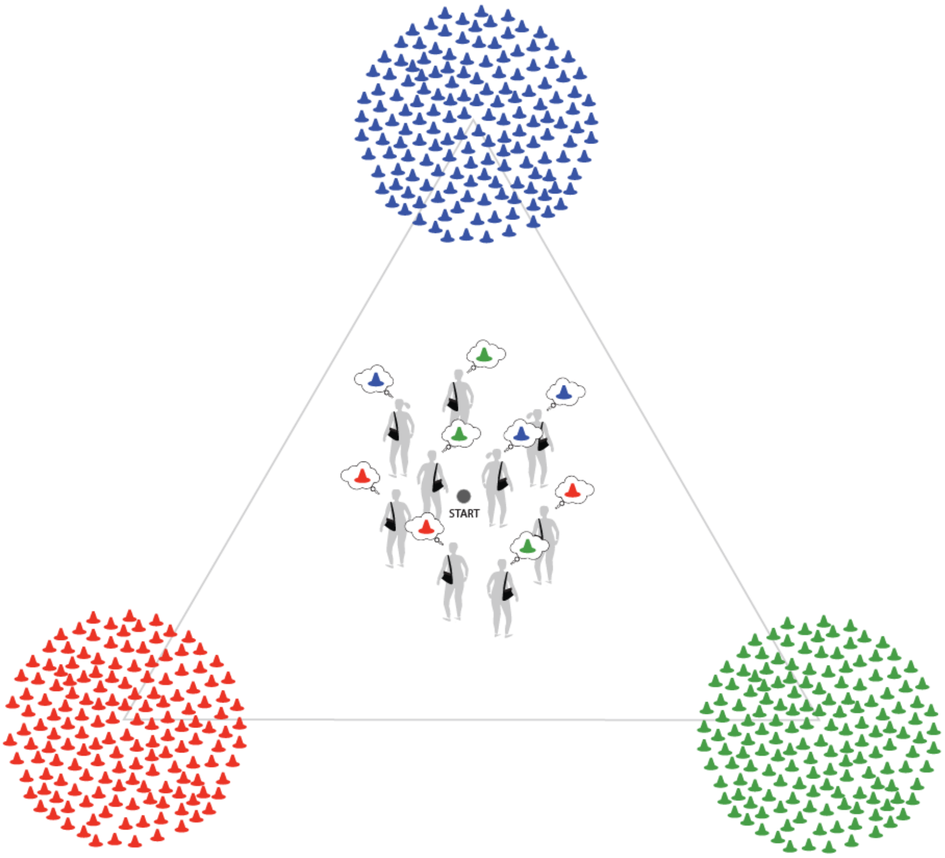

Figure 4. Spatial arrangement of patches and initial foragers positions in a real world task of collective decision making.

A second set of rules determine the expected tendency of players to cooperate or to compete in terms of different game modes. How much players are cooperating or competing will be quantified from the experimental data by fitting experimental measurements to the equivariant bifurcation model:

5. In the “democratic consensus” (DC) mode, in order to receive a reward players must reach an agreement about which is the richest patch by letting the majority of the players forage that patch. Because of Rule 2, it won’t be convenient that all the players forage in the richest patch. Foraging in poorer patches that are exploited by fewer people could lead to higher gains. We expect this game mode to favor cooperative social interaction, as reflected by increased verbal transmission of information regarding the quality of the patches and a faster convergence to group consensus.

6. In the “winner-take-all” (WTA) mode, only the team of players that collect the largest number of items per player gets the reward. A team is here defined as a group of players foraging in the same patch. In other words, teams must emerge during the foraging as a consequence of the collective decision making. We expect this game mode to favor competitive social interaction as reflected by little to none verbal communication, heightened vigilance between participants and less stable group behavior.

Finally, we can introduce minor strategic modifications to the game without letting the players know. For instance, we can provide false information about patch richness or we can introduce contrarians and zealor "actors" to assess how their presence affects the collective behaviors. Via these manipulations, the above rules, and the help of mathematical modeling, we hope to be able to isolate some key psychosociological parameters governing collective social foraging and decision making, as well as to identify spontaneously emerging psychopathological behaviors.

Among the limitations of this approach we stress that it is not always easy to translate between experiments and mathematics. For instance, it can be difficult to measure in experiments a parameter appearing in the model. It can also be difficult to check that the mathematical assumptions used in the model are verified in practice. Experimental situations can be limited by the number and availability of participants that can be tested simultaneously and include confounding effects of participant heterogeneity in age, socioeconomic strata, educational backgrounds, etc. These variables cannot be captured by the proposed mathematical framework. On the other hand, some features of the experiments are easily manipulable in the model but not in practice, for instance, the attitudes of single agents (i.e. zealots or random switchers).

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