Exploring collective intelligence in animal fission-fusion dynamics

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Abstract

Evaluating the information-processing capacities of collectives is important for understanding their origin and adaptability. We analyze fission-fusion dynamics, a flexible grouping pattern that responds in part to spatio-temporal variation in food availability, using naturalistic observations of spider monkeys (*Ateles geoffroyi*). We study individual decisions to follow others depending on their knowledge about ephemeral feeding sites, finding that information about available feeding sites spreads widely amongst the group, favoring the finding and grouping around trees with ripe fruit. We also extract from association data the networks of pairwise followership or avoidance, generating new data sets by simulation and finding that these networks give rise to adaptive global properties, such as a frequency distribution of subgroup size that effectively tracks the habitat-wide food abundance. We point at further research on how knowledge of available feeding sites complements synergistically among group members, such that by sharing information the group as a whole obtains a more complete picture of the dynamic foraging environment than each individual would obtain on its own.

A hallmark of living systems is their collective nature, from bacteria to brains to societies (Kim et al., 2021; Daniels et al., 2016; Krakauer et al., 2020). The way in which functional collectives of similar individual components form as a result of local interactions has been approached most successfully from the perspective of complexity and information theories. From these perspectives, collective behavior arises from individual-level microscopic states being coarse-grained in meaningful ways into certain macroscopic states and not others, which in turn feed back to the microscopic state, constraining the behavior of individual components (Flack, 2017). This implies the emergence of new functional properties that were not present in the components. How these properties arise and how they influence the behavior of individual components are still open questions.

One way to address these questions is by studying the networks that describe interactions between components, what role the external environment plays in shaping their structure and how they acquire the capacity to process and act upon information at the level of the whole system. Here we present such a study on the fission-fusion dynamics of groups of spider monkeys observed in natural conditions. Fission-fusion dynamics is a property of many animal groups that form temporary subgroups through the constant splitting and joining of individual group members, in many cases as a response to food availability (Aureli et al., 2008).

Distributed foraging in fission-fusion dynamics

Spider monkeys forage in subgroups that may travel independently from one another within large home ranges, yet coming together and splitting frequently (Ramos-Fernández et al., 2011). Because ripe fruit, their main food resource, is highly variable in space and time, it is possible that this grouping pattern allows them to share information (actively or passively) about the available fruit sources at a given time. This distributed foraging would require that individuals that knew about an available fruiting tree were followed by naïve ones, with the consequence that the group as a whole would find out about that particular tree in fewer visits than if each individual had to find it on its own (Palacios-Romo et al., 2019).

We performed diurnal observations in trees during their whole fruiting period, from the time they had only a few unripe fruits to the end, when no more fruit could be seen. During this time, we recorded all arrivals by spider monkeys, recording the identity of every visitor. We performed these observations in 30 different trees, only during the dry season, assuming that is the season when food is more limited and information about food is more valuable. Initially, all individuals were assumed to be naïve about the existence of fruit in the tree. As soon as an individual visited a tree, we assumed it became knowledgeable. When a naïve individual arrived with a knowledgeable one, we assumed there had been a transfer of information between them (Palacios-Romo et al., 2019).

With the results of these observations we constructed networks of information transmission. Fig.1 shows a network of followership to available feeding sources, where links go from a naive individual to one that knew about a feeding tree. These networks are cohesive and provide a way in which information about available fruiting trees could

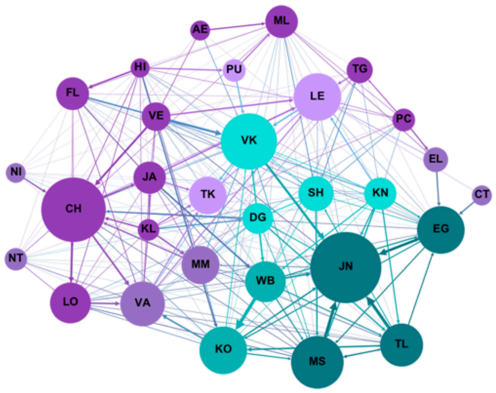

Figure 1: Network of followership from individuals that were naïve about the presence of an available fruiting tree to others that were knowledgeable. Directional link weight is proportional to the frequency with which an individual followed another. Size of nodes is related to how often they were followed to feeding trees when they knew about feeding sources. Purple colored nodes are females, blue colored are males, darker colors are adults and lighter subadults and juveniles. Taken from Palacios-Romo et al. (2019).

spread amongst all group members. To explore the effect of this network of visiting patterns on how many individuals already knew about the patch, we generated a null expectation of how individuals would arrive to a patch in the absence of information transmission. For this, we took the original data on visits and generated bootstrapped versions in which the size of subgroups was kept the same but the identities of individuals were randomized, thus eliminating the observed followership relationships but maintaining the size of the subgroups in which patches were visited. Indeed, the accumulated number of group members that already know about the patch increases more steeply with respect to the number of visits than in the randomized versions of the data (Palacios-Romo et al., 2019).

These results show that information about feeding sites flows in cohesive networks of local followership interactions and that this allows information to spread widely amongst group members. The grouping pattern of spider monkeys is flexible enough to allow them to to share partial knowledge (through the use of social information) about a complex foraging environment, effectively giving rise to a distributed foraging strategy.

Studying the networks of social influences

To further explore the way in which networks of social influences could underlie a collective information processing system, we used a two-year long database of subgroup membership, containing 5780 subgroup samples, to extract all probabilities that an individual would stay in or leave a subgroup conditioned on the presence or absence of every other individual in the group (Ramos-Fernandez et al., 2020). That is, regardless of the knowledge about foraging options, these networks represent the outcome of individual decisions to stay in or leave a subgroup depending on others. The collective effect of these networks is a frequency distribution of subgroup size, another global and adaptive property of spider monkey groups.

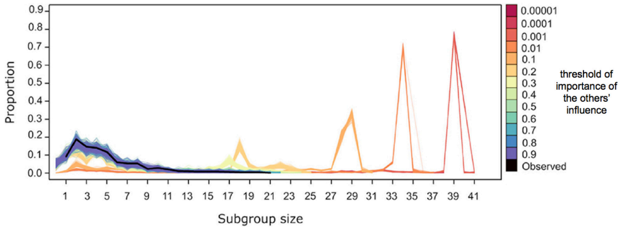

Figure 2: Frequency distribution of subgroup size, a global property arising from the networks of social influence. Observed (thick black line) and simulated from data under different assumptions for the influence of others on stay-leave decisions. Taken from Ramos-Fernandez et al. (2020).

Using these networks of social influences, we generate new subgroup size distributions by simulation, under different assumptions about how individuals integrate incoming influences from several individuals. Then, for the observed networks and the simulated data, we measure how well the resulting frequency distribution of subgroup size matches food abundance in the environment, using transfer entropies between the subgroup size and food abundance time series (Ramos-Fernandez et al., 2020).

Through this procedure we can artificially tune the way in which individuals integrate the influence from others and produce a subgroup distribution that matches the food abundance in the environment as well as the observed subgroup distribution. This suggests that the collective computation that the network of social influences is carrying out is indeed related to an adaptive global property like a flexible subgroup size, which is effectively tracking the variation in the foraging environment (Ramos-Fernandez et al., 2020).

A final demonstration of the collective intelligence shown by the group of foraging spider monkeys will be to measure the degree to which their pooling of information about the availability of fruiting trees is synergistic, *sensu* Bettencourt (2009). For this, we can measure the degree of overlap between individual utilization distribution areas (Smith-Aguilar et al., 2016) and infer, based on realistic models of fruiting species abundance and distribution, the sets of known trees available to each individual. Then, we can evaluate how redundant or complementary these different sets are, which would provide an evaluation of the degree to which collective intelligence arises by distributed foraging and the synergistic pooling of information.

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