Information Exchange Between Honeybees: Insight into the Self-Awareness of Group Collectives

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1 Introduction

1.1 Background

A particularly fascinating intersection between computation (Karaboga & Akay, 2009), human cognition, and animal behavior is the study of the honeybee hive. The field of honeybee research ranges a multitude of topics; including collective decision making (Thomas D. Seeley, 1999), information exchange (Biesmeijer & Seeley, 2005), and social structure (Seeley, 2009). A unique subset of cognitive science has suggested that honeybee hives are a representative model of the human brain, with individual bees acting as neurons and neuronal clusters which give rise to higher order decision making and planning. This phenomenon is particularly discussed in the swarm literature(Thomas D. Seeley, 1999).

Figure 1: Examples of honeybee swarms forming (in sometimes precarious locations).

Every spring, honeybee hives that have grown too large must split their members and locate a new nest site. More than half of the worker bees and the original queen will leave the hive, and a new queen will effectively "take over" the already existing nest. (Thomas D. Seeley, 1999). The venturing bees do not immediately relocate to a new nest site. Instead, they form a swarm (a large cluster of bees on a nearby landmark). Within this cluster, they will hold a 3-day long democratic debate, where the hive will collectively decide which nest site to relocate to. Scout bees explore the surrounding area and report back to the swarm, and communicate information about the potential nest sites via the waggle dance (communicative body movements and wing vibrations that signal direction and vitality of potential nest sites) (Biesmeijer & Seeley, 2005)[1]. Over the course of 3 days, the swarm reaches a unanimous decision on their intended nest site, and eventually lifts off in synchrony to form the new hive in the selected site.

Extensive research has investigated how bees select among the various nest sites. Key indicators of an ideal site include entrance area, entrance position, entrance direction, nest cavity volume, dampness of the site, and if another hive has previously occupied the site. (Thomas D. Seeley, 1999).

The current research has adequately outlined the behavior of information exchange between individual honeybees (Seeley, 2009). This includes pheromones, the waggle dance, the round dance, pipe sounds, and stop signals (Seeley et al., 2012). Throughout the swarm debate, 3 elements appear to be key for signalling information:

- **Waggle Dance**: Bees can communicate using an impressive motor pattern that signals “instructions” to sources of food or potential nest sites. The dance can signal both the direction and distance of the location (via “calculating” the angle of the sun). To convey enthusiasm, the dance will have numerous “waggle runs” (oscillating movements down the center of the dance space). The more waggle runs, the more profitable the site it is signalling about.

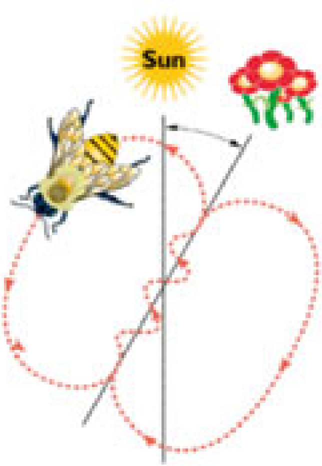

Figure 2: The dancer conveys the angle of the nest site in relation to the sun.

- **Stop Signals**: Competing bees will inhibit the dancing scout by ramming its body to force it to stop dancing. This is how a nest site is eventually unanimously chosen; all other competing sites are inhibited (Thomas D. Seeley, 1999)(Seeley et al., 2012).

[1]The waggle dance is also used in foraging to indicate food sources.

- **Pipe Sounds**: Once a nest site has been selected, worker bees emit a sound burst called a "pipe" when it is time to prepare for liftoff. In the hour leading up to liftoff, piping gradually increases to a climax at liftoff (Seeley & Tautz, n.d.).

1.2 The Question

The collective decision making of the honeybee swarm represents how individual processing units can give rise to higher-order behavior. This supports the analogy between social insects and the human brain. Using honeybees as a potential model, we can investigate the mechanism of information exchange between such individual processing units, and possibly gain insight about neural circuits and signalling. By investigating the capacity of the hive system, we can attempt to draw meaningful parallels between our own minds and the intricate behavior of the bees.

Such parallels can be explored via several different approaches to the problem. The problem becomes enormous when we consider topics like decision making, planning, information theory, network theory, *self-awareness* and *consciousness*. In essence, **I would like to know the similarities between the honeybee hive and the human brain.** In order to narrow down this topic to testable hypotheses, I will focus on testing the capacity of the individual processing units, in order to determine the flexibility and scope of the complex signalling phenomenon that we observe in bees. My work will focus on the specialization of individual bees to various stimuli (with potential for flexibility), and the possible contextual pressures on signalling.

More plainly, **What is the capacity of individual scout bee signals?** This question can be broken down into the following parts:

Are individual scout bees specialized to respond to particular stimuli (nest site quality)? → Push the capacity of the system and see if scouts respond to novel stimuli.

Are scout signals sensitive to context? → Manipulate hive conditions and see if scouts convey information differently for different conditions.

Each of these questions focuses on testing the capacity of the insect signalling system. An intuitive prediction would mandate that individual bees are simple input/output models with fixed action patterns and motor programs in response to relevant stimuli. This intuition would predict that individual scouts are, in fact, specialized to respond to a small range of stimuli and would not be affected by context. Such fixed and context-independent signalling would reveal a motor-programmed response to stimuli, and would reflect a limited range of actions for the individual processing units of the system.

1.3 Hypothesis

In general, I predict that the honeybee hive can serve as an appropriate model of the human brain. In fact, I predict that any self-organizing system is representative of any other. These systems have the potential to be represented in much simpler terms than traditionally done, and the honeybee hive can serve to do this. I predict context-sensitive and flexible self-organization of optimal systems. More specifically, this means that I expect the honeybees to behave in a much more flexible way than might be expected.

While the intuition may argue for basic processing and simple cognition in the individual honeybee, I suggest a different hypothesis. Animals often behave in highly optimal ways, due to the selective pressures that have shaped behavior (Alcock, 1993). It would be beneficial for an individual unit to be able to respond to multiple types of stimuli in an adaptive and flexible manner. If honeybee decision making has computationally produced analogous results to human models, then we could expect a more flexible and adaptive set of individual processing units.

I propose that scout bees will respond differently to novel stimuli, and convey this information with increased number of waggle runs. I also propose that scouts will behave differently when the number of bees receiving the signal is increased (e.g. when the context is different). Together, these might support the idea that the capacity of the individual processing units of the hive are more robust and responsive (flexible) than previously thought.

1.4 Alternate Models/Hypotheses

Alternatively, we might discover that the individual units of the honeybee hive behave in fixed action patterns. The scouts may be tuned to specific nest site qualities, and may not report any differently when a novel stimulus is included. This would mean that particular stimuli serve as "triggers" for motor output, which is not uncommon in animal behavior (Alcock, 1993). Additionally, the scouts would behave with no difference as hive conditions were manipulated. This would mean that information production by scout bees is not sensitive to context.

2 Research Aims

2.1 Aim 1: Specialization

I will aim to draw parallels between individual honeybees in a swarm and neurons in the human brain. In particular, I am interested in the degree to which scout bees are specialized (tuned) to the quality variables of potential nest sites. Current debate in neuroscience suggests that neurons may be highly flexible and not fixed in their tuning to stimulus. Honeybee scouts may function similarly; I predict that they would be active for the variables we have already determined to be relevant (*e.g. entrance area, entrance position, entrance direction, nest cavity volume, etc.*) but that they could also convey information about novel/modified stimuli as well. This would suggest that the individual honeybees are less "motor programmed" than we might expect for an insect, and could give us insight into the mechanism of collective decision making.

2.1.1 Hypothesis

I hypothesize that individual scout bees will respond with increased vigor (number of waggle runs) to some of the novel stimuli. While some novel stimuli may be ignored or seen as disadvantageous for a potential nest site, I expect a *different* response to the novel stimuli than without it. If the bees do not ignore the stimuli, then it might suggest that they are not only specialized for the particular nest site qualities that have been outlined in the previous research. It may even mean that they are entirely flexible in how they evaluate their environment in preparation to convey information. If individual scouts are not specialized, this may give us more reason to investigate the specialization (and flexibility) of individual neurons.

2.1.2 Methods

In order to test the specialization of scout bees to different nest-site variables, I will first collect data on how each of the variables are represented. I will test the responses for each of the known variables, and note how they change when they are ideal vs. non-ideal (e.g. Measure the number of waggle runs when the nest site has a southward facing entrance and measure the number of waggle runs when the nest site has a northward facing entrance.). Next, I will introduce novel features of a nest site, and tease out baseline factors that I have already observed. Novel features could include:

- Novel visual features, e.g. colors
- Novel visual features, e.g. shapes
- Novel smells
- Novel tastes
- Novel materials

I will measure the aggregate dances for both pre and post-stimulus introduction for the various combinations of manipulations. Measurements may include a binary value (did the scout bee choose this as a potential nest site/dance at all?), number of waggle runs, nest site selection (by entire swarm at the end of the debate), number of stop signals received, etc.

If we can demonstrate that scouts can convey information about novel stimuli, we can conclude that they are not fixed in what they can tune to.

2.1.3 Controls

It will be important to collect a "baseline agreement measure". We must see if individual scout bees each report similarly to similar stimulus (e.g. Will all of the bees convey the same information about a potential nest site?). If this is not the case, we might need to evaluate the distribution of agreement and take this into account when conducting our analysis. However, this ought to be a normal distribution and we can operate using the mean agreement index.

Initially, it would seem that we ought to control for the introduction of an object into the nest site at all. However, doing this would simply be another novel stimulus, which is what we are testing for. Therefore, the only controls needed are to only manipulate *one* aspect of the site at a time. If I am introducing a red patch, all other conditions (entrance direction, dampness, cavity size, etc) must remain constant.

2.1.4 Data Analysis and Interpretation

In order to investigate the effects of novel stimuli on information production, we can conduct multiple statistical tests on the data to tease apart any difference. This would include linear models to look at any effects of each novel stimuli on number of waggle runs or other features of the dance. We can also test using a binary value for if the nest site is chosen as a potential site or not. It could be the case that a scout *would* choose the site before the novel stimuli was added and *would not* choose the site if it included the novel stimuli. This would be a clear effect of the introduced stimuli on nest site selection. Basically, we would want our analysis to indicate a difference between groups in order to show that individual scouts could respond to various novel stimuli. This would support the hypothesis that they may not be specialized in what they respond to. If there is no difference in the dances conveyed for the nest sites (pre and post introduction of stimulus), then we might conclude that these scouts are tuned to specific qualities and do not expand further than these tunings (or that our novel stimuli were not adequate to push their responses to be different).

2.2 Aim 2: Context-Sensitivity

I am interested in the information exchange between scout bees and the swarm, and how this information might change depending on various factors. If a scout bee is responding to external stimulus with a fixed action pattern, their information ought to be the same for a particular nest site, regardless of other factors (number of bees responding to dance, number of other scouts, number of potential nest sites being danced for, etc.). I plan to investigate how the manipulation of hive-related factors might affect the information production of a particular scout bee. If an individual conveys different information about the same nest site when variables are manipulated (or as a function of the bees around them), then we might conclude that an individual bee produces information with the *hive in mind*.

2.2.1 Hypothesis

I predict that scout bees will behave differently when hive conditions are manipulated. Specifically, the scout bee may convey more urgency if there are not many potential nest sites in the surrounding area. Additionally, they may convey more urgently if there is a larger hive size. This would suggest that the individual units are "aware of" (or at least responding to) the context where their information will be *received*.

2.2.2 Methods

We need to test the consistency to which individual scouts represent the same nest site. We can introduce variables (number of bees "listening") and note if the dance changes considerably and significantly (depending on the relevant variables). Some important manipulations will include:

- Number of bees receiving the information
- Number of viable nest sites in surrounding area
- Number of other bees dancing for this particular site
- Size of hive
- Environmental conditions (e.g. weather, risk to swarm)

2.2.3 Controls

In these experiments, the nest sites will not change at all. The potential nest site will be held constant, but the context will be manipulated. We may want to control for fatigue if bees must dance multiple times in a short period. We would want to see if the dance changes naturally with *no* manipulation. If it does not, then we are safe to assume that any differences in dance are probably explained by the manipulation of the context (and not just natural fatigue or deterioration of dance). We will also collect the same baseline measures as seen in Aim 1.

2.2.4 Data Analysis and Interpretation

If bees are not responding to any change in context, we will see no difference in their dances throughout all conditions. We will test the effects of context changes on a variety of dancing factors, and determine if the bee changes their dance based on context. If there is a difference, we might conclude that the bees are actually considering the receiver of the information when they convey their dance. This could be a "self-awareness" task for the individual processing units of a group collective. If the individual units are "aware" of the context in which they convey information, it could be the mechanism by which the group collective achieves such context-sensitivity as well.

3 Conclusions

3.1 Addressing Open Questions in the Field

We have not yet determined the true parallels between social insects and the human brain, though this has been suggested throughout various literature. Additionally, we have not identified all of the mechanisms of communication and information exchange between a network of organisms such as the bees. While we have identified acute information signalling behavior (waggle dance, stop signals), there is still much to be gained from studying the bees. By pushing the capacity of the system, we can see the potential of insect behavior and learn about how information in a self-organizing network can be achieved efficiently. This work can contribute to the fields of animal behavior, decision making, networks, information theory work, formal systems, and perhaps even neuroscience. We may want to investigate genetic or morphological factors that allow for such information exchange as well.

3.2 New Data Changes How We Think About and Understand Behavior

Understanding the honeybees is relevant for a multitude of reasons. An obvious reason (though perhaps not so obvious as it has not been the focus of this work thus far) is to *identify potential causes or solutions to Colony Collapse Disorder*. There is a strong interest in "saving the bees", and any additional information may help us to achieve this. If it is the case that scout bees respond to novel stimuli in the ways that I have outlined, we may even be able to identify a potential disruption to their nest selection (various chemicals, locations near built environments, etc.). We could test a massive array of industrial chemicals as the novel stimuli of Aim 1 and see if this deters nest site selection or dwindles the options for viable sites.

Beyond this obvious problem, we can understand much more about information exchange within a model system. This extrapolates to fields like group collaboration, group decision making, urban planning, panic scenarios and procedures, effective learning, organizing systems, etc. If there is an ideal information exchange method that is hiding within the honeybee hive, we may have the opportunity to find it!

Furthermore, drawing parallels between the honeybee hive and the human brain (*or any formal system, for that matter*) could prove to be useful in understanding which directions to go in our research of cognition and neuroscience. Observing "natural" systems might inform our theories of our own minds. This, in turn, could lead to more efficient learning models, decision making, teaching methods, and improved group collaboration.

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