Hive Mind: The Correlation Between Honey Bee Dancing and Human Brain Decision Making

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And those who were seen dancing were thought to be
insane by those who could not hear the music.
— Friedrich Nietzsche

From folk to freestyle, ballroom to break, tango to twerk, dance has evolved and adapted to the different rhythms and beats of the times. Historically, dancing has been accompanied by melodies or music. The tune to which people danced influenced their movements and their corresponding meanings. Dancing has been interwoven with music for all of human history. Whether that be to the beating of bongos, the humming of throat songs, or the strum of string instruments, it is difficult to find movement without accompanying melodies.

For a long time, the music to which honey bees danced was unknown to humans. Why would such a simple insect dance for no obvious reason? What would be worth squandering such crucial energy? The act of dancing seems to defy evolutionary necessity at first glance. If honey bees' dancing provides no beneficial outcome, why would they continue to do it? As certain bees danced to an unfamiliar tune, we thought them to be mad or foolish. Unbeknownst to us humans, the peculiar dance of the bees was in fact a song — a song through movement.

The waggling bee dance was a mystery, until scientists examined it with regard to the whole hive. When a honey bee danced in their particular waggling figure-eight movement, the performer was always surrounded by nearby viewers. These viewers were not watching out of mere boredom, but instead they were learning specific information from the variations of the dance. Without the advanced vocal chords or mouths humans are accustomed to, honey bees do not have the luxury of speaking or singing to one another. Nevertheless, these small insects have evolved to dance as a means of communicating with the rest of the colony. Their characteristic waggle dance follows the rhythm and rhyme of their language, and the unmelodious music to which they dance is the key to their communication.

The enigma of the dancing bees may prove to help scientists solve more complicated questions. As honey bees with relatively miniature brains are able to exhibit advanced communication skills, they serve as a rather accurate and accessible simplified model for studying human brain function. Humans have 86,000 neurons for every one honey bee neuron, which renders studying the human brain almost impossible ("Brain Anatomy"). The exact responsibilities of different brain regions are still not fully understood. Fortunately, honey bees display social behaviors parallel to how neurons communicate and exhibit similar brain functions to humans despite their limited brain size. Both the cognitive qualities of the individual honey bee and how they interact as a super organism to come to a decision are akin to the human brain. These attributes make honey bees ideal models to study further the intricacies of the human brain.

Honey Bee Basics

The honey bee differs from other species of bees in that it exhibits a unique colonial sophistication. Known as Apis Mellifera Linnaeus, and part of the order Hymenoptera, which includes wasps and ants, honey bees are distinguished by "having two pair of wings that are veined in cross angles creating a cell-like pattern" (Richman). Bee species are characterized by the length and shape of their tongues as well as the distinct pattern of veins on their wings. All species undergo a "four-stage metamorphosis from egg, larva, pupa, to adult," yet out of the roughly 20,000 species known, only approximately 500 species are social and form colonies. Honey bees are one such social species which form colonies containing a few hundred to 80,000 individuals. The colony of honeybees carries out complex behaviors unseen in other species

(Richman). Despite having “fewer genes than almost any other species,” their efficient genetics are “capable of colonial ‘loving’, hive development, nest cleaning and communication” (Hathaway). Each colony is composed of three types of bees working together to maintain the hive: the worker, drone, and queen.

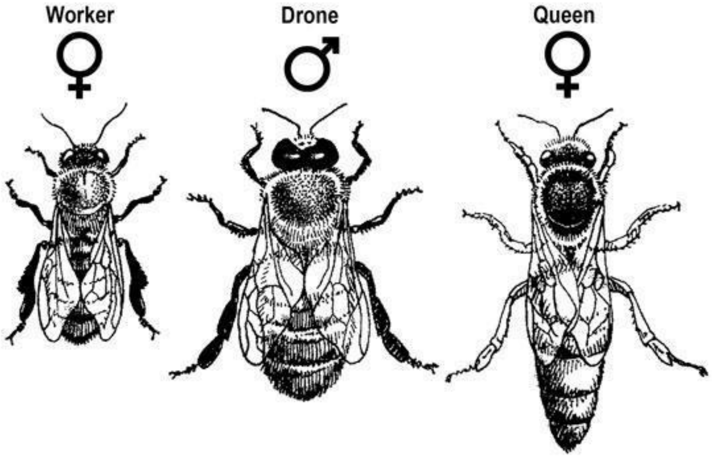


Image 1. Honey Bee Types

Types of Honey Bees

Each type of honey bee has unique physical attributes designed for their specialized role. The worker bees and queen bee are both female, but they differ structurally. Anatomically, worker bees are the smallest of the three and have wax glands in their head and pollen sacs on their hind legs. Worker bees are able to activate their ovaries and lay unfertilized eggs, but they only do so in rare circumstances. Drones, which are the only male bees in the hive, have little purpose other than to mate with the queen. They are bulkier than the workers but not equipped with wax glands, a stinger, or pollen sacs to collect nectar. If they serve their purpose they die in the act of mating; if not, they either die of old age or are kicked out of the hive at the end of a season to starve (Richman).

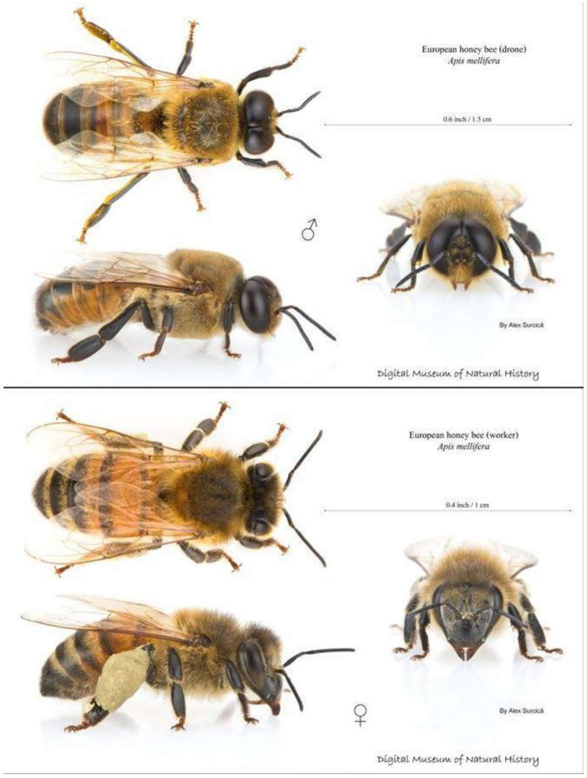


Image 2. Differences Between Worker and Drone Anatomy

Queen bees also lack the structures of the worker, and, instead, they have a long abdomen, short wings, and a larger body. Solely, they are responsible for mating and laying fertilized eggs. Owing to her important role, the queen lives on average for several years, whereas the workers live approximately one season (four to five weeks). Alongside laying roughly “1,000 to 1,500 eggs per day,” the queen’s presence promotes a cohesive community in the hive. She is the mother to every bee in the hive, including her future successor. The queen determines the sex of her offspring by either fertilizing or withholding sperm from the egg, resulting in workers or drones respectively. While the queen is not the leader in the sense we know of, the hive is doomed if another pupa is not raised as the next queen (Richman). These three types of bees interact together to form a social network of thousands of sentient individuals.

Image 3. Queen Bee Surrounded by Workers

Honey Bee Brain

Although a fraction of the capacity of the human brain, the honey bee brain is able to process advanced input to perform complex tasks. Owing to the limited space in the bee brain, the “brain allows the analysis of behavioural control and neural functions to be carried out at the level of the single neuron.’’ Research surrounding the brain function of the bee has shown that “single neurons [are] sufficient for a cognitive function.” Compared to other insects, the honey bee brain (roughly one million neurons) is larger and more absolute. With their advanced neural function, they display advanced navigational skills, complex social behaviors, and a bountiful cognitive capacity. The source of their social intelligence lies in the workings of their neurons (Menzel 758-60).

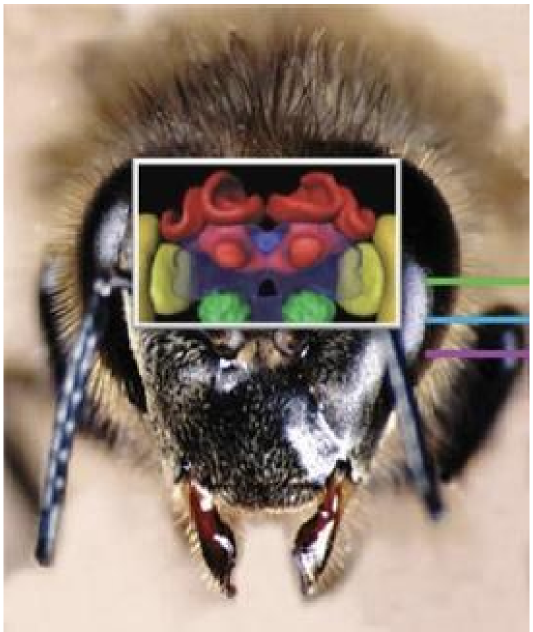


Image 4. A Colour-Enhanced Depiction of the Honey Bee Brain

The central complex in the bee brain controls many of the bee's navigational and social interactions and aids in their ability to learn. Found also in other insects, the central complex underlies an insect's ability to navigate with respect to their ''orientation and movement in the environment'' (Barron and Plath). Composed of only "approximately 3,000 neurons," the central complex is able to process spatial information, sensory input, visual cues, and position, as well as being the decision making center in the insect brain. The central complex differs from typical brain structure and is composed of a "matrix of 16 to 18 vertical columns, intersected by several horizontal layers, creat[ed] by tightly woven neural processes" forming a unique crystalline structure. Researchers study the individual neurons in the central complex, which process information to make a decision, in order to better understand navigational control. The central complex even has the capacity to cope with a certain amount of displacement and uncertainty, such as wind and weather variations, when navigating (Heinze and Butler). Factoring in these interferences creates a more reliable and accurate route for the honey bee.

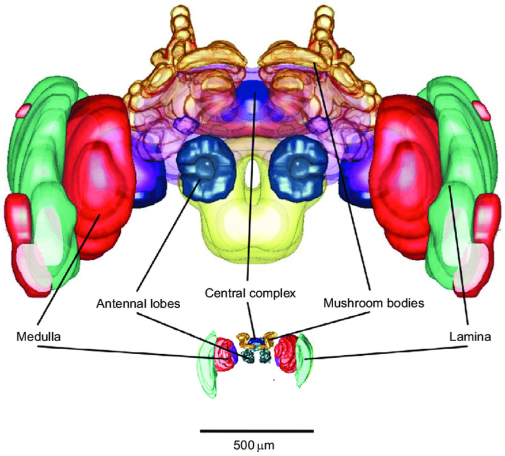


Image 5. Honey Bee Brain Anatomy

In order for honey bees to navigate to and from the hive, they must also rely heavily on the sun's revolution and orientation. The central complex, alongside decision making, takes input from the sun and factors it into a honey bee's navigational knowledge. The ability to determine the position of the transiting sun is crucial for honey bees to forage and communicate their findings with others. Across the width of the central complex, some of the neurons have evolved to "respond to celestial polarized light" which are essentially specific cells tuned to an angle of polarized light which "correspond to a particular position of the sun along the horizon." This allows the honey bee to subliminally pick up the position of the sun with respect to its heading by merely recognizing which neurons light up. This "internal sun compass" is highly precise and is one key component of a honey bee's spatial orientation (Heinze and Butler).

Other inputs regulated as part of an individual's spatial awareness are not processed in the central complex. The neck of the honey bee is responsible for computing its orientation in relation to gravity by sensing a pressure difference from the head to the thorax based on the incline the thorax droops. The greater the thorax angles down from the neck, the greater the pressure difference which signals to the honey bee that there is a greater gravitational pull. Alongside gravity and the sun's position, the honey bee is also able to adapt to changing time throughout the day and seasons. The neurons perceiving solar polarizations communicate with those monitoring circadian rhythms "suggesting a possible locus for time compensation of the celestial compass" (Barron and Plath). With the constant adjustment of factors to create a reliable orientation in their space, honey bees are able to hold a detailed memory of their paths and communicate it with others.

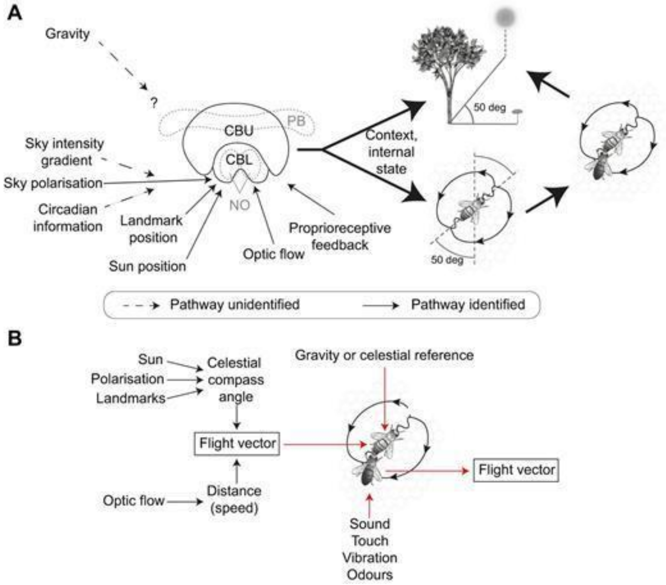


Image 6. External Input Utilized in Honey Bee's Spatial Orientation. Section A Depicts the Various Inputs Regulated in their Brain Which Allows Them to Dance at an Accurate Angle Depicting the Location of the Nest Site or Food Source. Section B Illustrates the Multiple Variables Which Determine the Flight Vector of the Waggle Dance.

Spatial memory is first formed on an insect's initial foraging journey. By conducting a series of planned and structured flights orienting around the nest, they "examine the nest from many different angles at increasing distances" in order to produce a reliable memory of the nest surroundings. Once they have solidified their reckoning of the nest area, the insects are ready to forage at greater distances and use several strategies to return home. A widely used method for bees and ants is route following, which relies on the insect to memorize the specific route from a food source to the nest and continue on such route if the food source is profitable. This method is only reliable if the environment has substantial features, for it does create more sound forms of memory (Heinze and Butler).

However, the most popular strategy is path integration, also referred to as dead reckoning. As an insect flies or walks in search of food, it "monitors its movement and tracks its change in direction…and continuously updates an internal memory of the distance and direction of the nest." Once the insect is ready to travel home, the data collected is transformed into a "home vector" which allows the individual to follow a straight line to the home nest. This strategy is highly precise, especially in the species with an internal compass and/or odometer, such as honey bees (Heinz and Butler). Relying on their own spatial memory, honey bees have evolved unique ways of conveying this information to others.

Working memory is often considered a component of higher intelligence in species, and honey bees are one such insect able to communicate and to evaluate their memory. Despite having a relatively small brain, the wellbeing of the hive relies on the intercommunication of its members. The cooperative actions of the honey bees are reliant on each of the individuals and their "experience inside and outside the community." The shared memories of the bees allow the group to "develop expectancies about future events and to base their decisions and their communicative behaviour on the expected outcomes" (Menzel 758-62). The experiences of the individual are shared to promote the welfare of the hive.

Honey Bee Social Structure and Communication

The social structure of bees is not that of a dictator or monarch but instead exhibits a social network with aspects similar to humans. Each member carries out a specialized task which aids in the collective welfare of the hive, not solely for the benefit of the queen. A research experiment at the University of Illinois Urbana-Champaign "discovered that there are detailed similarities with the social networks of humans" and bees. Contrary to the popular belief that honey bees behave in unison to accomplish a collective goal, bees do exhibit individual differences and preferences. Originally, the study planned to examine "honey bees as a convenient social insect to help us find ways to measure and think about complex societies" but instead discovered honey bee workers have preference for the bees with which they interact (King-Klemperer).

In the experiment, the researchers measured trophallaxis, the transfer of liquid food by mouth between insects, because the "bees are physically connected to each other by proboscis contact during trophallaxis." The bees are in a controlled hive and tagged with small barcodes distinguishing the individual and their interactions. The individual connections amongst them were not uniform and varied from short to long depending on the bees interacting. The interactions are equated to a "virtual spring" to measure the attractiveness between bees, where a strong spring holds two bees interacting for longer and a weaker strength allows bees to quickly break the connection and seek out others (King-Klemperer).

Image 7. Honey Bees Exhibiting Trophallaxis

From this data, the researchers "developed a theory where bees exhibited an individual trait of attractiveness that could be likened to human interactions," as seen in preferences for friends and family over strangers. The theoretical model was compared to human datasets "revealing similar patterns" and indicate a universality of honey bee and human interactions. This experiment is one of many to suggest honey bees operate a sophisticated colony which may shed light on "simple and universal regularities" in complex societies and elucidate how advanced "communities emerge from very different social roles and interactions" (King-Klemperer). As part of the social network, it is necessary to regard each honey bee as an individual working for the good of the group.

Honey bees have evolved into a eusocial group relying on altruism and kin selection in the individual to benefit the group. According to Merrium-Webster, eusociality is "living in a cooperative group in which usually one female and several males are reproductively active and the nonbreeding individuals care for the young or protect and provide for the group." Honey bees fit the criteria and exhibit codependency whilst still maintaining autonomous preferences. Typically bees are envisioned living in harmony together and caring for one another equally, but recent studies have shown their altruistic tendencies are largely due to kin selection. In these circumstances, altruism is "defined as reducing one's own reproductive output to help others reproduce" and kin selection as a biological tendency toward altruistic behaviors in order "to pass genes to the next generation." In a normal hive, the queen lays the eggs and therefore passes on her genes to her offspring. These matrigenes promote altruism in the female worker bees, since they are all working together to raise their siblings. When the queen dies or leaves, the patrigenes of one of the ten-plus males the queen mated with take lead and causes the workers "to selfishly compete with one another to lay eggs" in order to benefit their own gene line. Termed "intragenomic conflict" bees exhibit both altruism and kin selection depending on the stability of the colony. Thus, due to the variability in patrigenes in worker bees, they are able to exhibit individual preferences as well as behave altruistically (“Conflict”). The amalgamation of individual and group good is a primary tenet of a super organism.

Honey bees act as a super organism, coordinating themselves to react with external stimuli and make decisions. American biologist, William Morton Wheeler, coined the term “super organism” to describe a group of individuals acting as a “single ‘being’ equivalent to a vertebrate animal” or a “single integrated living organism” (Tautz 3). Other organisms are known to display similar characteristics such as some termites, fish, and birds. Bee colonies are “composed of a large number of fully autonomous individuals that interact with each other to bring forth a collective response” to a stimulus. Acting as a cumulative unit does not negate the efficacy of an individual, but more so illuminates the duality of the honey bee to act as a lone organism or part of a super organism. Occasionally, the needs of the individual contrast with the needs of the group. The misalignment of a few bees is “an inherent property of collective decision-making” and may result in a future benefit. In particular, some worker bees have been observed returning to a prior feeding site after the majority of foragers have moved on to a different one. These outliers may serve to remind the colony of food sources that may become profitable again, while the bulk of their resources are at the current profitable site (Sloat). The duality of the honey bee is analogous to the cells which make up an organism or neurons which make a decision.

Honey Bee Decision Making

Decision making in the hive is a complicated process and involves more than just one bee. Primarily, decision making comes into play when the insects are searching for a food source or new cavity for a hive. There are certain criteria for a sufficient nest site. Chiefly, the nest must have adequate room to hold combs, rear brood, and store honey while also remaining secure and protected from predators and weather. Additionally, the nest is more ideal when it resides near profitable food and water sources. Time is also a factor in the process. In the event of a swarm, a natural occurrence due to overpopulation or a lack of a reliable nest or resources wherein the queen and thousands of members fly together in search of a new nest site, time is crucial. The bulk of a swarm resides on a branch or crevice while worker bees depart in search of new nest options to relay to the rest of the group. Every hour a swarm remains exposed, their energy reserves deplete and the chances of survival decrease. Additionally, if the insects do not come to a unified agreement, "a split decision…lead[s] to swarm fragmentation" which often results in death for all parties (Seeley and Visscher 102). Coming to a decision requires the bees to use an efficient language to communicate with all the members.

Image 8. A Swarm Resting on a Branch

The Waggle Dance Language

The primary language amongst bees is dancing, or more specifically, waggle dancing. This particular type of motion "can be described as a repeating figure-of-eight movement performed on the vertical surface of the comb…[where] between the two loops of the figure eight, the bee takes a stride and leans forward, vibrating her wings and waggling her abdomen rapidly from side to side" (Barron and Plath). Performed on the hive, other bees witness the dance to learn of new hive sites or food sources to check out themselves. The foragers, composed of worker bees, report back "heterogeneous information — knowledge of superb, mediocre, and even lousy sites" to the rest of the hive using the waggle dance. While not all discoveries are acceptable or even eligible, the "large set of alternatives" increases the chances of finding the most promising site (Seeley and Visscher 110). While the exact origins of the dance are unknown, the dance has evolved into a highly precise and succinct form of communication.

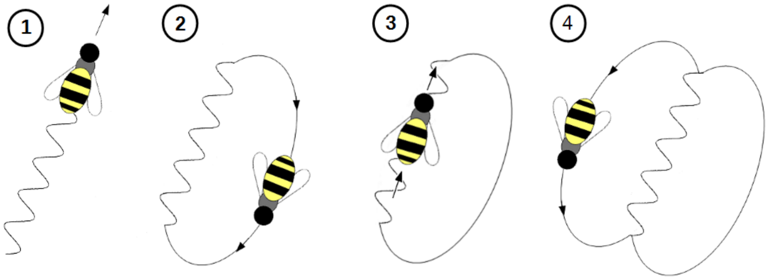


Image 9. Waggle Dance Diagram

What began as an excitatory run in the direction of a foraging site has evolved to be a highly accurate method of communication. The waggle dance is believed to have originated from a simple "re-enacting of the departure direction of the forager bee." In essence, the first dances are believed to be a "symbolic enactment of the foraging flight" wherein the direction of the promising sight is conveyed to surrounding bees. This pattern may have simply started from a bee performing her departing flight vector while still on the comb prior to foraging. Later, the characteristic figure-eight pattern evolved "as a mechanism to enable the dancer to hold a position on the comb for multiple circuits" in order for the information to be relayed to a greater number of surrounding bees. Once the honey bee completes the waggling portion of the dance, she circles around to repeat the movement. The vibrations of the dancer's abdomen as well as sound pulses from her wings are adapted to enhance the visibility of the dance in “low-light environments” (Barron and Plath). Once the rudiments of the waggle dance were formed, social bees fine tuned the movement to broadcast more information about the flight.

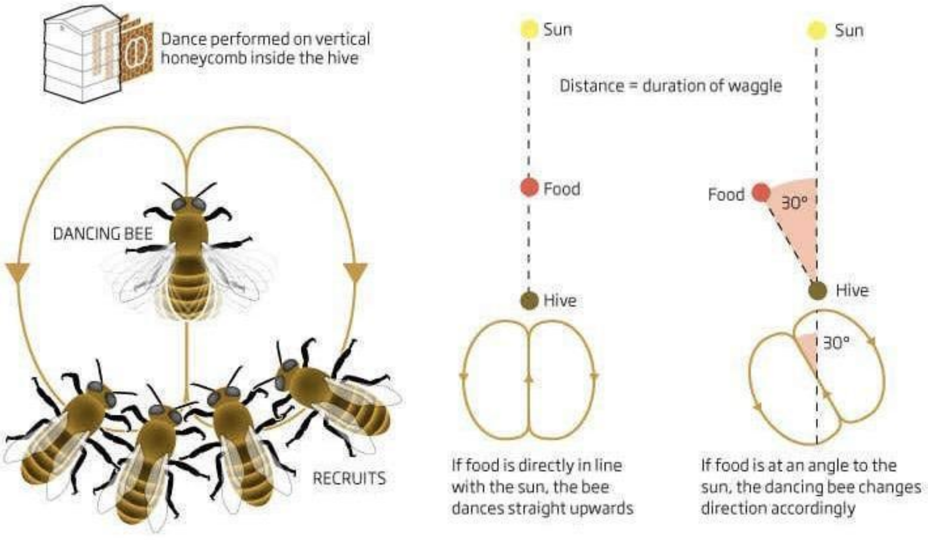


Image 10. Waggle Dance Interpretation

Direction of the waggle dance correlates to the direction of the profitable source as well as its angle relative to the sun. The central complex picks up the angliture of the sun and integrates that information into the insect’s waggle dance. The honey bee uses her memory of the sun’s angle relative to the food source to position herself at the same angle when performing her dance on the comb. As the sun’s position moves, the performers are able to adjust their dance according to the information received by their central complex and the amount of time which has passed. By mimicking the angle of the site relative to the sun’s position, onlooking bees are able to pick up the relayed quantitative information “considered the signal of direction” and follow the same path themselves (Barron and Plath). The onlookers “integrate this information into spatial memory” which allows them to traverse the direct route to the aforementioned location (Menzel 766). Direction alone is not enough to inform the hive of the profitability of a site, however.

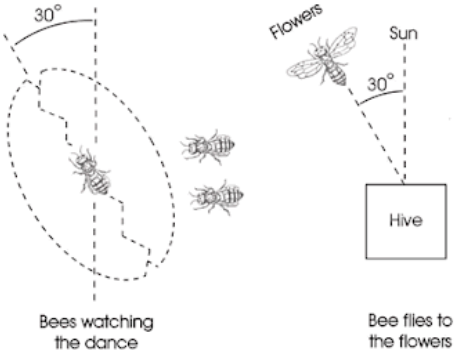
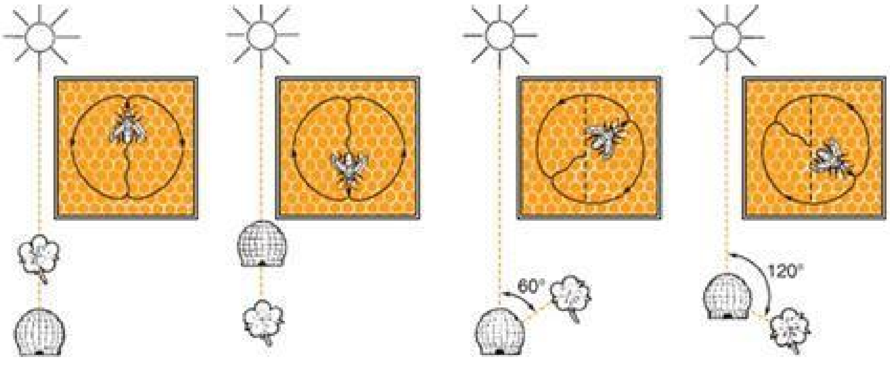


Image 11. Angle of the Waggle Phase of the Dance

The intensity of the waggle dance correlates to the viability of the prospective site. Enthusiasm over an ideal location compels the individual to “dance with passion, making 200 circuits or more and waggling violently all the way,” whereas a forager informing others of a mediocre site dances fewer circuits less intensely. The enthusiasm of the bee with the better site inspires more bees to explore her find. In this sense, “enthusiasm translates to attention” and attention translates to increased visiting of the site. When viewers go to inspect the site and like it, they return to the hive and conduct the same dance, inciting others to visit (Zimmer). Alongside the intensity and angle of the dance, the duration expresses multiple pieces of information about the potential site.



The bee runs up to tell other workers to fly toward the sun. It runs down to tell them to fly away from the sun. The number of runs in a given time indicates distance.

The angle at which it runs gives the angle of the food source relative to the hive and the sun. The drawings do not show that the scout is surrounded by workers that follow its movements.

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Image 12. Further Analysis of the Angle of the Waggle Phase of the Dance

Duration of the waggle phase of the dance and the duration of the dance circuits both represent different aspects of the spot. The waggle phase occurs between the two loops of the figure-eight wherein the honey bee shakes her abdomen. The duration of this phase “correlates with the distance of the resource from the hive.” As the length of the waggle phase increases, the distance between the hive and the site increases proportionally (Barron and Plath). This allows the surrounding bees to gain a sense of distance as well as direction. Analogous to a vector, the length and angle of the waggle phase provide crucial information on the whereabouts of the site. The duration of the dance circuits corresponds to the validity and appropriateness of the option. Longer dances inevitably enlist more honey bees to check out the spot, which leads to the best sites accumulating more and more dancers promoting them (Taylor). The process of rejecting locations and promoting others eventually leads to a unanimous decision for a particular nest site.

Coming to a decision through dance communication relies on individuals to participate in the group decision making process. Initially, hundreds of foragers report back to the hive with varying options and perform their dance. The individuals with a more intense waggle and longer circuit repetitions inspire more bees to explore their finds. Those with weaker and shorter dances have fewer supporters which eventually leads to the waning of those particular dances. In order to avoid sticking to a bad decision, the “decaying dance” allows bees to pursue a more advertised route until the lesser sites are forgotten (Zimmer). While in the hands of the worker bees, the group decision making is “a leaderless process…consist[ing] of a friendly competition among the different groups of dancers representing the different potential nest sites.” This friendly competition of foragers consists of groups or coalitions “of scouts committed to a particular site” which compete “with other coalitions for additional members drawn from the pool of uncommitted scouts." The honey bees are trying to achieve a majority decision in this winner-take-all situation (Seeley and Visscher 104-10).

Image 13. Honey Bees are Tagged with Barcodes to
Digitally Count Headbutting and Nest Site Selection

Apart from the positive feedback from new dancers and nest options, negative feedback plays an important role in decision making. Implicit negative feedback is "negative feedback through the absence of positive feedback." When foragers return from an insufficient site, they are less likely to recruit others, and thus the site is eventually forgotten. Explicit negative feedback is uncommon in social insects, with one of the few exceptions being the honey bee. The stop signal is a term describing a vibrational signal emitted by a bee onto another. This short signal, only "150 ms with a fundamental frequency of around 350 Hz," is issued whilst headbutting another bee. This headbutting paired with the vibration communicates to the impacted individual predation, competition, or a lack of interest in their advertised location (Borofsky et al. 3). The first wave of stop signals is typically "sufficient to suppress recruitment for this particular food source." As the headbutted individual's dance begins to wane, one stop signal may not be enough to completely dissuade the individual from continuing her dance. "As a reinforcement for the first wave," a second, less intense, stop signal pursues until a threshold is reached wherein the bee is convinced to stop advertising their particular site (Borofsky et al. 15). The stop signal as a means of negative feedback helps speed up the decision making process.

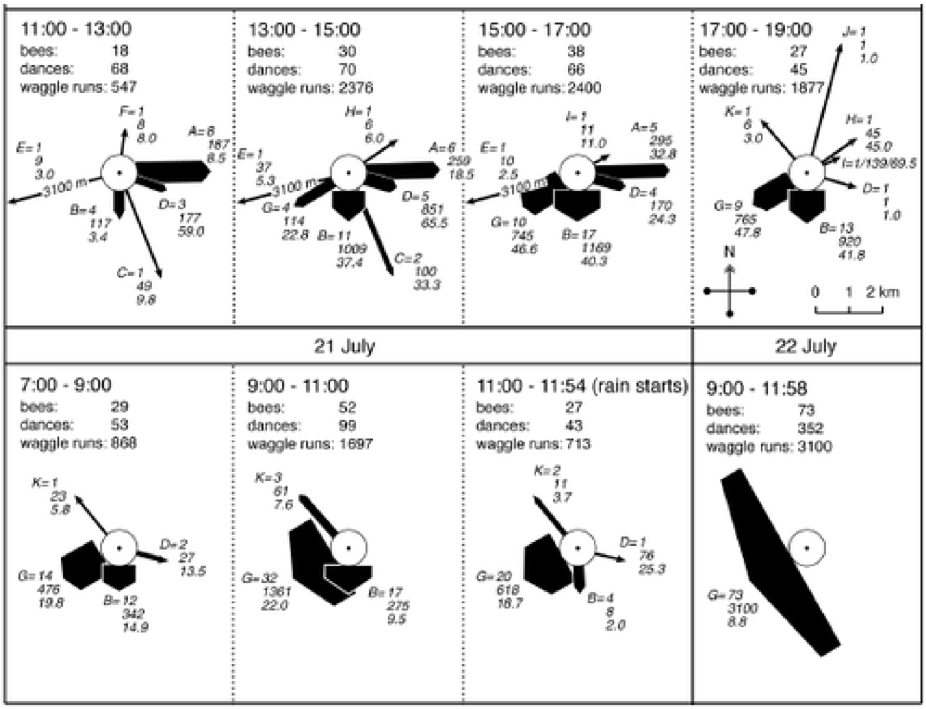

Image 14. Vectors Correspond to the Direction and Number of Supporters for a Specific Nest Site. The Wider the Arrow, the More Dancers supporting that specific location.

The culmination of positive and negative feedback eventually results in a unanimous decision. Coalitions compete until only a few remain, and these groups, "each advocating a different choice, integrate positive and negative feedback, until the accumulated positive feedback in one of the populations exceeds a threshold." Once the threshold is crossed, the associated group and their choice wins the decision. This multifaceted process "allows individuals with limited information to globally reach a consensus" and decide on the better choice in less time. Decision making as a group based on information from individuals allows the hive to function as a society or super organism while only being "governed by simple feedback mechanisms" (Borofsky et al. 1-2). Honey bees are not the only organisms which rely on a medley of individual information to reach a unanimous decision.

How Primate Brains Make a Decision

The human brain consists of billions of neurons firing signals to one another. Contrary to popular belief, more than 10% of the brain is always in use, as it is the key organ in the regulation of bodily processes, such as memory, emotions, thoughts, motor skills, hunger, touch, temperature, etc. The brain is not a muscle and instead is composed of fats, water, protein, carbohydrates, and salts. Weighing approximately three pounds, the brain uses more energy than any organ relative to its size ("Brain Anatomy"). Amongst all of the other necessary functions, the brain is also the center for decision making, wherein individual neurons obey certain laws to reach an optimal decision (Sloat).

How Cells Communicate

Neurons are the biological cells which "perform complex computations that underlie our behavior" by communicating with one another. Each neuron is comprised of dendrites, a soma, an axon, and an axon terminal. The soma is the cell body and contains a nucleus and the cell's organelles. Dendrites branch off the soma similar to antennae in order to "receive and process signals from the axons of other neurons." These receptors can form multiple clumps on the soma, called dendritic trees. The axon is a long, tubular structure insulated by fatty rings known as myelin. The tail-like structure is joined to the soma at the axon hillock. On the other end of the axon is the axon terminal where many fiber-like structures send chemical or electrical signals to surrounding neurons. The synapse is the location between one neuron's axon terminal and another neuron's dendrites where the signal is passed. The two communicating neurons do not touch each other, instead, the signal leaps from one neuron to the other (Vandergriendt and Zimlich). In essence, a signal is detected in the dendrites and then travels through the body and axon of the neuron until it reaches the axon terminal where it can be passed on to a neighboring neuron.

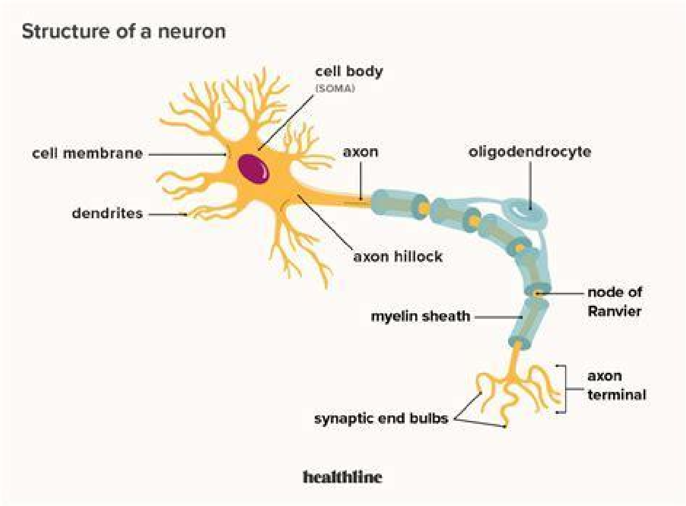

Image 15. Neuron Anatomy

Communication through synapses requires signals to follow a specific path from one neuron to the next. As a nerve signal reaches the end of the axon terminal, “it must trigger the release of neurotransmitters which can carry the impulse across the synapse to the next neuron.” The neurotransmitters act as microscopic messengers which are received by the dendrites of the nearby cell. The nerve signals are akin to an electrical current, wherein the wires are like neurons and the plugs and outlets are the synapses. Synapses consist of three main regions: 1) like a messenger, the presynaptic ending resides on the end of the axon terminal and contains the neurotransmitters; 2) between the two nerve cells where the transmission of the signal takes place is the synaptic cleft, which is where the message is passed over; 3) the receiving end of the dendrites composed of receptors is the post synaptic ending, which is where the message is accepted (Cherry, “What is a Synapse”). The complex messaging system of the neural signals adhere to specific biological laws.

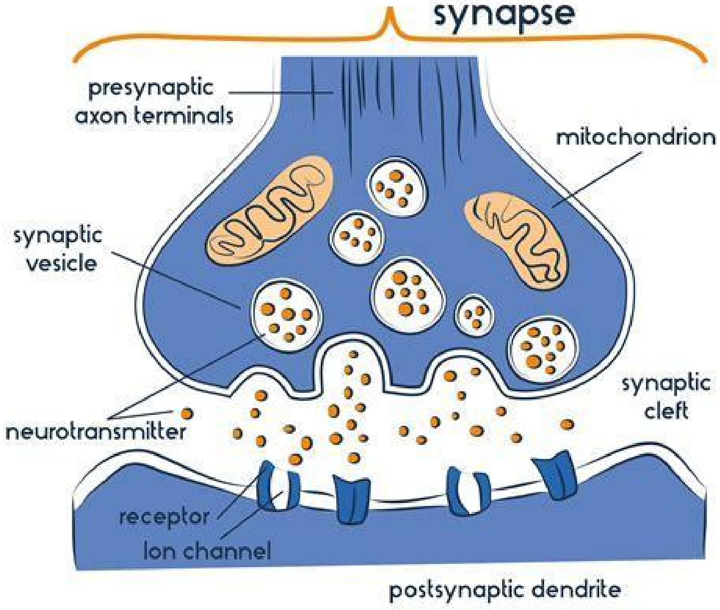

Image 16. Synapse Diagram

Psychophysics and Feedback Mechanisms

In all creatures with a brain, specific neurons are activated in response to certain stimuli. The activated neurons are either prompted to signal surrounding neurons to activate or not based on the strength of the stimuli in comparison to prior or nearby stimuli (Akre and Johnsen). Decision making based on perceived stimuli can be binary or multi-faceted. A binary decision, commonly used in yes-or-no questions, relies on a unanimous decision, whereas a multidimensional decision eliminates the poorest of choices while keeping in mind the best options (Borofsky et al.). The vast majority of decisions made are subconscious and based on what the individual perceives/experiences. Simply put, "the ways in which animals perceive and measure stimuli from the social and physical environment guide nearly every decision they make." Sensory perception, stimulus intensity, and the number of choices all factor into how the individual neurons fire and respond to signals, ultimately leading to a decision (Akre and Johnsen).

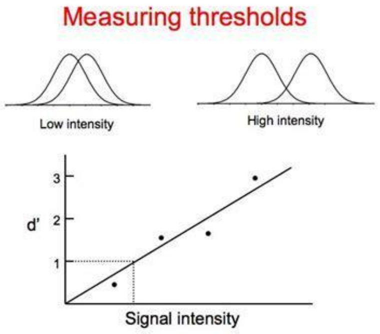

Image 17. Difference Threshold and Perception

The interplay of three psychophysical laws eventually leads to a decision being made. The biological laws of neuron cells are based on the "relationship between stimulus intensity and its perception in the human brain." Psychophysical laws explain this relationship by quantifying the intensity of reactions to a variety of stimuli (Reina et al.). The term "psychophysics" was coined by Gustav Fechner in the mid-1800s who examined "the relationship between incoming physical stimuli and the responses to them." In order to study this relationship, most psychophysicists measure the absolute threshold of detection, the absolute threshold of identification, and the difference threshold between two stimuli ("Psychophysics"). Research on these thresholds led to the formation of three biological laws of neurons.

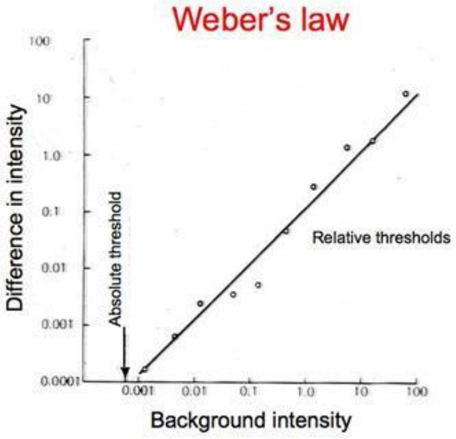

Image 18. Weber's Law Graph

Weber’s Law concentrates on the difference threshold between multiple stimuli. This principle of perception “states that the size of the just noticeable difference varies depending upon its relation to the strength of the original stimulus.” In other words, the ability to perceive a change in a stimulus in comparison to itself or others depends on the weight or strength of the original stimulus. This law demonstrates that “our physiological experiences of the world are relative.” If someone is holding a small stone and picks up another small stone, they are likely to notice a difference in weight. Although if someone is holding a large rock and picks up another small stone, they are less likely to notice a change in weight (Cherry, “What is Weber’s Law”). To quantify these findings, “the minimum difference between two stimuli…is a constant ratio of the original stimulus” (Reina et al.). Differentiating options is necessary to come to a quick and accurate decision.

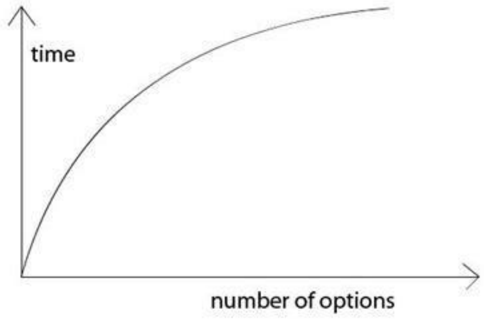

Image 19. Hick-Hyman’s Law Graph

Hick-Hyman’s Law centers around the difference threshold and decision making. This principle “states that the more choices a person is presented with, the *longer* the person will take to reach a decision.” Quantitatively, the time spent coming to a conclusion increases logarithmically relative to the numbers of options considered. In this sense, “the increase in time taken becomes less significant as the number of choices continues to increase,” and conversely the time used to make a decision is more significant with fewer options. Hick-Hyman’s Law primarily applies to choices which are equally viable. If someone is given the option to choose one rock when presented with three similar looking rocks, they will have to reason which two to eliminate. If someone is asked to choose one rock when presented with fifteen equally tenable rocks, the process of reasoning which fourteen to eliminate will take much longer than eliminating two. In the same thread, if they had to choose one rock out of eighteen, the time taken to deliberate their choice would not be much longer than eliminating fourteen. The time spent eliminating poor choices is significantly shorter than the time spent withdrawing equally profitable options ("Hick's").

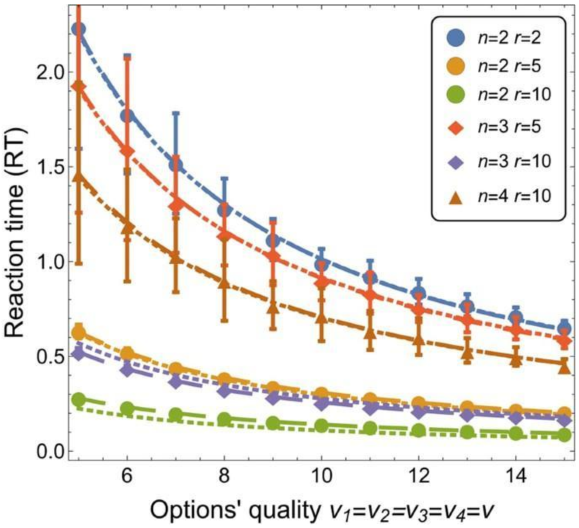

Image 20. Piéron's Law Graph. The Mean Reaction Time (RT) Decreases as the Option Quality Increases.

Piéron's Law was developed as a means to quantify the intensity of a stimulus and the correlating mean response time. There are two tenets of Piéron's Law discovered in initial studies. Chiefly, the mean response times of the individual exposed to a controlled stimulus "were found to decrease as a power law (exponentially) with the decreasing stimulus intensity." In this sense, the more potent or prominent stimulus, such as a bright light compared to a dim one, the quicker the brain responds. The low intensity of the dim light results in a smaller difference threshold which makes it harder for the brain to register the stimulus. Alternatively, Piéron's Law can "extend to the more general notion of discriminability in (perceptual) decision-making." Decision making with respect to Piéron's Law can be regarded as a "two-alternative forced choice," wherein the decision is between putting forth a response or withholding one, such as firing a neuron or not (Maanen et al.). If the stimulus is subtle and lacking intensity, the brain will take much longer to respond and may not take notice at all. The distinction between the two can either eliminate or promote options. In addition to psychophysical laws, neurons also respond to feedback mechanisms.

Negative feedback in neurons is prevalent in the course of making a decision. Implicit as well as explicit forms of negative feedback work congruently to promote or discard an option. The simpler and more subtle implicit negative feedback takes form in neurons which are not activated by a stimulus or a signal from a neighboring neuron. A nearby neuron may signal another neuron, but if the intensity of the signal is not strong enough the neuron will not continue to relay the signal. Conversely, explicit negative feedback involves neurons taking action instead of remaining idle. In the event of a rogue neuron firing, there are such "inhibitory neurons [that] are dedicated to sending only explicit negative feedback." These inhibitory responses or stop signals prohibit certain neurons from signaling which allows the brain to react quickly to stimuli on a group level and minimize the burden on the individual neurons. The amalgamation of positive and negative feedback eventually leads to "competing neuronal assemblies [which] garner winner-take-all decision making dynamics" (Borofsky et al.).

Reaching a Decision

In essence, reaching a decision relies on the interplay of neuronal feedback, psychophysical laws, and thresholds. "Separate populations" of neurons "accumulate evidence for alternative choices; when one population reaches a threshold, a decision is made for the corresponding alternative.” The aforementioned threshold varies depending on the number of choices, speed, and accuracy of the decision being made. The goal of many decisions is to choose the optimal alternative in the shortest amount of time in order to minimize the energy expended in the process. The most efficient method relies on individual neurons reacting to nearby signals to cohesively promote or reject an option with minimal awareness of such an option. This allows individual neurons to work as a group to collectively come to a decision (Marshal et al.).

Comparison to Social Insects

Honey Bees Acting as Neurons

Social insects, such as some bees and ants, display communal behavior rarely seen in other communities. Honey bee workers are individuals who collect information and share it with the rest of the hive through dancing. The duality of the individual to interact with its environment as a single organism and use its information to benefit the entire super organism strengthens its similarities to a neuron. Neurons are not privy to the inner workings of the brain; instead they simply fire signals to nearby cells or do not. “Just as each bee doesn’t understand [the workings of the hive] each neuron doesn’t understand” the larger picture of the brain (Taylor). In this way, “a single visual neuron is like a single scout. It reports about a tiny patch of what we see, just as a scout dances for a single site” (Zimmer). Both neurons and honey bees exhibit duality in their individual and group functions without formally understanding their role in the whole community. In actuality, the “mind is an emergent property of neurons working together” just as “the decision on where to build the new nest is *emergent* at the hive level, based on very simple individual bee behaviors” (Taylor). While individuals do not comprehend all that goes on in the whole, researchers are able to use their parallel qualities to learn more about each other.

The decision making process in primate brains is parallel to that of social insect colonies. Prior to the understanding of honey bee decision making, no group of organisms has been known to operate similarly to a single brain (Reina et al.). The complex process honey bees use as a collective to unanimously decide on a nest site or keep multiple profitable foraging sites in circulation "has been compared to the way a brain's different parts are involved in cognitive deliberation." The brain, composed of trillions of individual neurons firing and communicating with one another, seems random and disorganized at surface level; "when you consider a swarm one bee at a time this way, it starts to look like a heap of chaos." Like neurons, each individual insect with its tiny brain only perceives its immediate surroundings. It is only when "thousands of honeybees … pool their knowledge" that they can "make a collective decision about where they will make a new home, even if that home may be miles away." Combining the individual's collective knowledge "minimizes the cognitive load on individual foragers" whilst maintaining a eusocial society without a primary leader. This self-organized system enables the facilitating of "efficient and effective group decision making by optimally aggregating the relatively limited cognitive capabilities of each individual" (Sloat). This super-organismic analogy to neurons is reinforced by the shared methodologies and processes used to make a decision.

Honey Bees Adhering to Psychophysical Laws

Psychophysical laws have been expressed in "a large number of organisms at diverse levels of biological complexity" to "characterize the relationship between stimuli and the organism's response." Such organisms include unicellular beings, human beings, and most things in between. It was not until recently, however, that "groups of individuals, in our case honeybee colonies, considered as a single super organism, might also be able to obey the same laws" (Reina et al.). Neurons essentially argue with each other to reach a consensus by crossing a threshold. Likewise, honey bees in a colony argue to “coordinate their responses to external stimuli according to strict rules” in order to efficiently and effectively come to a group decision. The process in which individual bees communicate with one another is comparable to how many individual neurons interact with each other (Sloat).

Following up on the psychophysical laws exhibited in brains during decision making, honey bees have been documented demonstrating the same behavior dynamics. Both individual neurons and worker bees do not “obey psychophysical laws themselves but do so as part of the whole” (Sloat). In other words, “no individual explicitly encodes in its *simple* actions the dynamics determining the psychophysical laws; instead it is the group as a whole that displays such dynamics.” Whether a neuron is firing neurotransmitters to a nearby cell or a worker bee is informing surrounding foragers of nest sites, the individuals relay the information they have gathered or received in order for the group to react based on a collection of information (Reina et al.).

When faced with two potential nest sites of differing quality, it does not take long for the waggle dancers to weed out the poor profitability site in favor of the higher quality one. The choice between a bountiful or a barren location is straightforward. However, when they are presented with two nest sites with commensurate qualities, the bees have a harder time deciding which nest to choose, because “the smaller the difference in quality between two options, the more difficult it is to make the decision.” Calculating the difference thresholds to make a decision between two similar or dissimilar alternatives is precisely how a colony of honey bees or cluster of neurons behave according to Weber’s Law (Sandoui).

When confronted with two nest sites of equal quality and desirability, the colony takes longer to decide which one to inhabit. This scenario with minimal “difference in quality between both options" results in a greater competition between the two groups of dancers advocating for one of the nest sites. The two groups of nest proponents waggle with intense enthusiasm and length hoping to inspire others to enlist in their cause. Owing to the two nests having equally beneficial characteristics, both groups of dancers will continue advocating for their site until one of them gains enough supporters to reach the threshold and win the decision. This is opposed to being given the choice between two poor sites, which takes less time to choose due to the lack of redeemable qualities to support the choice. Honey bees are prone to continue dancing intensely in support of high profitability sites so their information is spread to a wider range of nearby individuals. They are more likely to cut their dull dance short for lower quality sites either due to a lack of interest by other bees or from receiving the stop signal. This "confirms the validity or Piéron's Law, which states that humans make decisions quicker when the two options they're confronted with are of high sensory quality, compared with when they are of a low quality" (Sandoui). The difference in time spent advocating for poor or profitable nest locations follows the curve of Piéron's Law, wherein the more intense a stimulus the quicker neurons will respond and/or carry on the signal to others (Sloat).

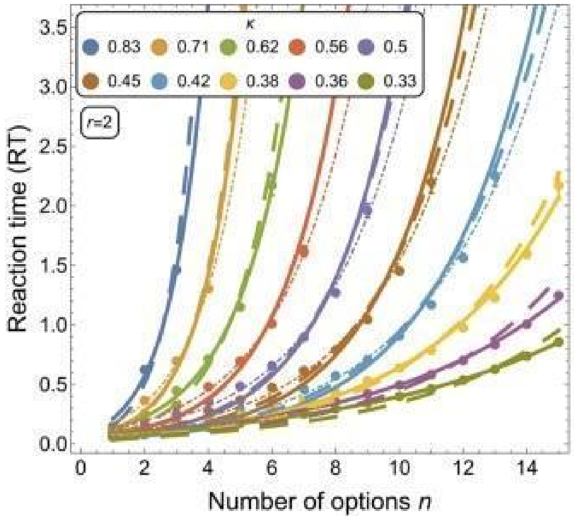

Image 21. Hick Hyman's Law Graph. As the Number of Options *n* Increases, the Reaction Time (RT) Increases Logarithmically.

In addition to regarding the quality of the nest sites, factoring the quantity of options also plays a role in the time it takes to make a decision. When presented with twenty possible options for a hive location, the foragers take each one into consideration and only reject options as a group. Dwindling the less favorable sites is relatively quick, but nevertheless, each decision comes from the group reacting to a conglomeration of individual information. When faced with only five nest options, the time spent deliberating and checking out each potential location is shorter. This adheres to Hick-Hymans's Law, which states that "the brain makes decisions more slowly when the number of options increases" (Sloat). In essence, the same psychophysical laws primate brains follow are also demonstrated by a colony of honey bees when making a collective decision.

The similarities between the processes of neurons and honey bees to come to a decision may prove to enhance our understanding of the human brain. Numerous parallels between bees in a colony and neurons can be traced, helping us to "understand and identify the general mechanisms underlying psychophysical laws" (Sandoui). With new documentation of biological groups displaying psychophysical laws, researchers are able to conduct "further investigations…between neuroscience and collective intelligence [which] can highlight analogies that could help better to understand both systems." As honey bees are small in size and great in number, they are ideal to study the biological mechanisms that our brain also exhibits in order to garner a better understanding of our own complex neural systems. Using honey bees' group adherence to psychophysical laws, scientists are able to use colonies as a new tool to research neuronal thresholds, for "the behaviour of bees selecting a nest is simpler than studying neurons in a brain that makes decisions" (Reina et al.).

Using Honey Bees to Further Understand the Brain

Honey bees defy the previous “notion that insect behaviour tends to be relatively inflexible and stereotypical.” Glancing at a nearby insect, many onlookers expect them to be relatively simple and unaware. Instead, insects in a colony display advanced communication, cognition, social, and spatial behaviors. All of their complex actions are moderated by a brain limited in size and complexity, which “offer[s] an opportunity to study the relationship between behaviour and cognition in neural networks that” are a fraction of the size of our own (Menzel 758). Honey bees in particular are “attractive for such a comparative approach” due to their complex behaviors enacted by such a miniature brain. Their rich cognitive repertoire has led to researchers reconsidering what factors are necessary to explain cognitive differences in organisms with varying brain size. Previously, it was assumed species with larger brains, and thus more neurons, display higher cognitive behaviors than those with smaller brains. Intuitively, this makes sense. An elephant would appear to have a more complicated brain structure and display greater cognitive behavior than that of an ant, yet the findings of honey bee behavior have challenged this assumption (Menzel 766).

Using knowledge of honey bee memory formation and spatial memory, investigations are being conducted to translate the neural correlates underlying these complex behaviors into neural circuits found in human brains. In other words, “the small size of the bee brain offers the opportunity to trace neural plasticity to specified neural circuits and to single neurons” (Menzel 758). The human brain is vast and little understood, but the miniaturized and somewhat simplified mechanisms in the bee brain may enable us to better understand the inner workings of specific regions of our brain. Utilizing which neurons in the bee brain detect and store components of particular spatial memories can help researchers garner a greater knowledge of which parts of our brain's neural circuits also retain specific memories. Little research has been published utilizing the advanced cognitive capabilities of the honey bees, but numerous studies are in the works based on using their "mini-brain" as a streamlined model of our brain. The goal is to use their "knowledge of insect brain structure [to] allow us to understand how comparatively small (and simple) brains can generate complex patterns of behaviour and act as a gateway to understand more complex brains and their evolutionary development" (Smith 1). Owing to the honey bee brain's ability to control advanced social, spatial, and communication behaviors with a relatively small number of neurons, researchers today are able to decipher functions of the human brain previously misunderstood (Borofsky et al.).

Conclusion

Owing to the parallels between honey bee and human decision making processes, these insects serve as a simplified, accessible model to further comprehend the intricacies of the human brain. Honey bees' exhibit duality, both as a cognizant individual capable of acquiring comprehensive information and as a part of the whole hive sharing details through dance and working harmoniously to reach a decision threshold. The decision making process of the hive follows the same psychophysical laws present in human neural networks which reinforces the similarities between the two. The two disparate decision making processes rely on reaching a threshold based on the number of supporting bees or neurons. Examining the first known example of psychophysical laws displayed in group behavior may allow scientists to broaden their understanding of animal cognition and, in turn, correlate their findings to the workings of the human brain.

Concrete studies have yet to be conducted using the honey bees as a simplified cognitive model, but the overwhelming similarities between the two have excited many scientists to consider the opportunities of doing such. The honey bee colony serves as an accurate and accessible microcosm for scientists to further research the intricacies of the brain. Now privy to the chorus of the colony, we understand and perhaps may utilize the rationality behind the dance of the honey bee.

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Image Bibliography

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Image 4 https://journals.biologists.com/jeb/article/220/23/4339/33674/The-evolution-of-honey-bee-dance-communication-a

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