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Rakesh Kumar Behera
Division of Entomology, ICAR-Indian Agricultural Research Institute, Pusa, New Delhi, India

Sanjay Kumar Pradhan
Department of Agricultural Entomology, University of Agricultural Sciences, Bangalore, Karnataka, India

Swagatika Sahoo
Department of Entomology, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha, India

Nikita Negi
Department of Agricultural Entomology, Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh, India

Corresponding Author:
Rakesh Kumar Behera
Division of Entomology, ICAR-Indian Agricultural Research Institute, Pusa, New Delhi, India

Small brain, big smarts: An insight into learning and cognitive abilities of insects

Rakesh Kumar Behera, Sanjay Kumar Pradhan, Swagatika Sahoo and Nikita Negi

Abstract
Insects are crucial for maintaining a healthy ecosystem. They play a significant role in pollinating plants, which is directly related to human food security. Although insects have tiny brains, recent discoveries have challenged conventional wisdom about what is possible with their ostensibly straightforward nervous systems. Insect brains are not simple. Understanding their learning and cognition mechanisms and the depth of their perceptual worlds gives their conservation and research ethics a unique perspective. Recent studies have shown that various insect species possess previously undiscovered cognitive abilities that go beyond the framework of traditionally studied simple associative learning and spread into the higher stages like concept learning, social learning and numerical cognition. Understanding these concepts and mechanisms will certainly help in revealing the mystery of brain functions and give us an edge in the artificial intelligence.

Keywords: Cognition, insect brain, conditioning, concept learning, social learning

Introduction
The brain has been the most intriguing part of any organism. Scientists have been fascinated by it for ages to know more about it. In this context, a popular hypothesis is- “big brain, big smarts”. It argues that species with greater brain sizes, particularly in the case of humans, are smarter which is supported by our evolutionary history that shows our brain size has increased considerably in tandem with our intelligence and cognitive capacities. Though there is a division of opinions, most scientists believe that a larger brain is needed for greater complicated tasks. Human brains weigh between 1.3-1.4 kilograms and contain an estimated 85 billion nerve cells, but the brain of a honeybee weighs only one milligram having less than a million neurons. For this kind of obvious reason, the tiny neural system of insects has led us to conclude that they are incapable of performing various complicated tasks over the years. But, recent study findings, on the other hand, suggest a different viewpoint. Insects have some of the most important cognitive abilities, including the ability to ‘invent’ new foraging techniques, communicate and learn from one another, facilitating the cultural spread of newly acquired information.

Insect learning and cognition
Learning and cognition are at the heart of every complicated task that an organism does. Learning is the process of obtaining knowledge or skill, whereas cognition is any mental function or information processing, such as thinking, remembering, visualising, and so on. In general, learning and cognitive principles entail classical conditioning, concept learning, selective attention, social learning, numerical cognition etc. (Giurfa, 2015; Perrry *et al*., 2017) [12, 23].

Classical conditioning
(Pavlovian conditioning) is a learning method which shows autonomous learning. It involves pairing a physiologically potent stimulus with a neutral stimulus. A neutral stimulus is known not to show any response before conditioning, but after conditioning, the neutral stimulus results in a response that is similar to the one elicited by the potent stimulus. Classic conditioning has been studied in the honey bee, *Apis mellifera*, using olfactory conditioning of the proboscis extension response (PER). Individually hungry bees extend their proboscis in response to a sucrose solution stimulation of their antennae (the unconditioned stimulus).

The bees acquire an elemental link between scent and sucrose reward when a neutral odour (The conditioned stimulus) is forward-paired with sucrose, and they demonstrate conditioned PER to later presentations of the odour alone (Takeda, 1961; Giurfa *et al*., 2012) [29, 9].

Concept learning is one type of non-elemental learning. It requires the transfer of the independent physical nature of the stimuli (e.g., colours, shape, size) and relies on relations between objects like- 'same as', 'different of', 'above/below' and 'on the left/right'. It has been observed that honeybees could form 'same' and 'difference' concepts. They learned how to execute 'delayed matching to sample' tasks responding to a matching stimulus and 'delayed non-matching to sample' tasks responding to a different stimulus (figure 1). Upon training, for colour and scent, bees learnt not only how to do a delayed match-to-sample job in the smell domain, but also how to transfer this ability to the visual domain (Giurfa *et al*., 2001) [13].

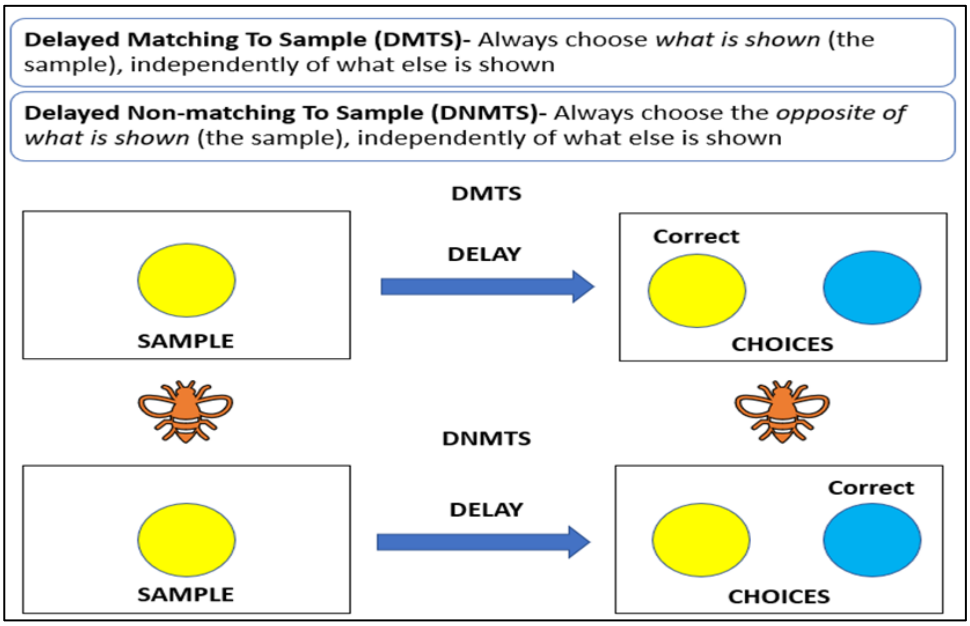

Fig 1: Delayed matching to sample and delayed non-matching to sample

Selective attention refers to the nervous system's ability to prioritise the processing of information that is most important. In basic terms, it focuses on a single stimulus regardless of what else is seen. Absolute conditioning is when single stimulus is rewarded (A+, where + indicates the presence of a reward), whereas differential conditioning is when one stimulus is rewarded in the presence of other stimuli that are closely related to the rewarding stimulus (A+ vs B–, where – represents the absence of reward). Investigation regarding the effect of differential conditioning on honeybee colour discrimination revealed that the bees learnt and could distinguish the training stimulus from a novel stimulus (Giurfa, 2004) [10].

Social learning is prevalent in nature and animals use social learning to propagate innovative behaviour patterns occasionally presented by a single "innovator" among group members. Some of these behaviours can be observed in primates and birds. To state some of these interesting examples, Japanese monkeys wash sweet potatoes before eating (Hirata, 2008) [16], chimpanzees use grass twigs as tools for termite fishing (Goodall, 1986) [14] and birds are seen to be able to open milk bottles (Lefebvre, 1995) [18]. Researchers were interested in such animal events because they intended to identify the basic evolutionary elements of the cultural processes that characterise us as human.

Insects possess some of the key cognitive skills needed to "create" novel foraging strategies, communicate, and learn from one another, promoting the cultural dissemination of recently learned information (Chittka *et al*., 2022) [6]. Bumblebees (*Bombus terrestris* Linnaeus) could learn a non-natural object manipulation task by employing string pulling to obtain a reward in an artificial flower under a Plexiglas table. In the study, it was observed that only two individuals out of a hundred 'innovated' and instinctively pulled the flower from beneath the table. On the other hand, the majority of naive bees learned the task by watching a skilled demonstration. This clearly showed that certain bumblebees can learn to pull strings on their own, although this skill may be extremely rare due to the highly explorative "personality" of these individuals or just "luck" in the course of random exploration (Alem *et al*., 2016) [2]. The learning of the string-pulling process involved several associative mechanisms, including local enhancement (observers are drawn to the location of their conspecific), stimulus enhancement (attraction to the item handled by the demonstrator), and perceptual feedback (a type of trial-and-error learning in which action causing movement of the rewarding object towards the animal produces positive feedback for continuing that action).

Numerical cognition is a branch of cognitive science concerned with the cognitive, developmental, and neurological foundations of numbers and mathematics. While many animals are capable of employing cognition for hunting and decision-making, it is debatable if any non-primate creature might achieve numerical cognition, such as accurate number and arithmetic functions, such as solving addition and subtraction issues. Such a capability would need intricate working memory and long-term rule-based memory management. However surprising as it may sound, a recent study on numerical cognition using honeybees (*Apis mellifera* Linnaeus) as the test species, demonstrated that honeybees were able to learn addition and subtraction tasks. They were trained with two different colours in which one meant for addition and the other one for subtraction. The bees correctly solved the task after the training period revealing their numerical cognitive abilities (Howard *et al.*, 2019) [17].

Cognition in hymenopterans

Research studies have been mostly done on hymenopteran insects to know about the various forms of sophisticated cognitive abilities. *Cataglyphis* sp., a desert ant, is known for being able to navigate vast distances without leaving chemical traces, which evaporate in the desert heat. In the visual modality, studies on the paper wasp, *Polistes fuscatus* (Fabricius) showed that individual recognition is done by memorising the yellow-black patterns on the wasp faces (the so-called 'masks') or abdomens, which operate as efficient markers of social hierarchy (Avarguès-Weber *et al.*, 2011; Sheehan *et al.*, 2016) [3, 26]. In some studies, it is noted that bees learn by watching other pollinators (even from a distance), about which flowers to visit for nectar and its extraction process (Dawson *et al*., 2013, Alem *et al*., 2016) [8, 2]. In a study the positive emotions in bumblebees were investigated, where the bees were trained such that, they were taught to approach a rewarding stimulus and stay away from a punishing stimulus (Perry *et al*., 2016) [2]. Bumble bees, *B. terrestris*, are influenced by other conspecific members when sampling unfamiliar flowers, and land on unknown flowers where other bees have been. Likewise, if accompanied by experienced foragers, naive bees abandon an unrewarding species and switch to a more rewarding alternative more quickly (Avarguès-Weber *et al*., 2011) [3].

Like vertebrates, adjust their choice behaviour according to their certainty of success, bees were trained in a visual discrimination task in which they could leave a trial without making a decision or receive a reward for making the right choice, quinine for making the wrong choice (Perry and Barron, 2013). Bees could classify visual stimuli based on their global orientation and distinguish between different patterns and shapes. They can also classify visual patterns according to their bilateral symmetry of flowers, landscapes, plant stem etc. (Avarguès-Weber *et al*., 2011) [3]. In a recent study it was noted that, when ants raid other insect colonies, such as termite nests, they will rescue nestmates from collapsed tunnels or predators. Individuals who have been rescued have a greater chance of surviving and will eventually benefit the colony (Frank *et al*., 2017) [15].

Cognition in other insects

Apart from bees and other hymenopterans, there are several insects that show complex cognitive abilities in nature. It is discovered that split-brain cockroaches have multiple navigation systems in their brains that are combined into a coherent whole (Pomaville and Lent, 2018) [22]. The kissing bug exhibits significant adaptability in learning spatial avoidance (Minoli *et al*., 2018) [20]. Associative learning is studied in *Drosophila* sp. larvae where they learn to distinguish between rewarding & unrewarding stimuli and do not seek out the rewarding stimulus, along with they also learned to avoid the unrewarding stimulus, exhibiting the existence of multiple simultaneous memory traces resulting from the same learning (Schleyer *et al*., 2018; Chittka *et al*, 2019) [24, 7]. Numerous contributions focus on odour learning. For instance, *Drosophila* sp. larvae that have been taught to distinguish between two odours indicate the principles of odour mixture processing based on how they react to combinations of the two trained odours (Chen *et al*., 2017). When subjected to stressful situations beyond their control, fruit flies, *Drosophila melanogaster* (Meigen), exhibit a state akin to 'learned helplessness' in humans, with less movement and more frequent periods of resting (Batsching *et al*., 2016) [5].

Mechanism

In several studies, it is examined which specific brain areas, neural networks, and genes enable behavioural complexity in insects (Chittka *et al*., 2019) [7]. The primary brain structure for storing and retrieving memories is the mushroom body. It is underlined how GABAergic neurons play an important role in inhibitory signals in several brain areas of moths, crickets, and bees (Ai *et al*., 2018) [1]. Protein and gene specific distinctions can be used to identify between different types of mushroom body cells (Suenami *et al*., 2018) [28]. It is shown through modelling that the central complex, a small region of the brain found in ants and other insects, can connect landmark and vector memories and also a sun compass (Le Moel *et al*., 2019) [19]. It was demonstrated that the circadian clock controls the expression of the immediate early gene Egr-1 of bee mushroom bodies by focusing on the learning of a certain time of the day as a predictor of food reward (Shah *et al*., 2018) [25]. The small brains of insects restrict their attention to the point where they can only search for targets by scanning the scene sequentially rather than taking in the entire visual surroundings simultaneously (Spaethe *et al*., 2006; Perry *et al*., 2017) [27, 23]. The central complex has recently been identified as a potential location for the seat of consciousness in insects due to its function in fusing external input with internal simulation of the environment (Barron and Klein, 2016) [6]. Thus, engineers and computer scientists are beginning to recognize insects as a model system for researching how intelligence can be achieved with tiny nervous systems (Chittka *et al*., 2019) [7].

Conclusion and future prospects

Insects have inspired scientists for millennia because they provide access to a wide range of processes and behavioural organisations. Various types of advanced cognition have been postulated in recent experimental research, particularly in social insects. Insects are therefore promising species for further unravelling neural networks, learning, memory, and cognitive mechanisms. Neuro networking, which is analogous to programming in certain ways, can serve as the foundation for artificial intelligence and robots. It will also aid in unravelling the nature of intellect and brain function, which remains a mystery in many ways. Understanding the brain mechanisms of memory and cognition will undoubtedly aid the medical sector in the fight against diseases like dementia and also in disease diagnosis as observed recently in covid detection. Insects, although having a fewer number of neurons, have shown more sophisticated behaviours. A large brain may be required for more control, but it does not always imply greater intellect. The task that necessitates a huge brain is yet unknown. Indeed, the brilliance of life shines brighter in the creation of smaller masterpieces rather than larger ones.

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