Automatic monitoring of hive activities as indicators of the health status of bee colonies

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Summary:
Evaluating the health status and development of bee colonies not only requires expert knowledge, it is also extremely time consuming. To address a number of open questions, it would be helpful if we could continuously extract signals from the hive electronically. We have initiated a study that focuses on analyzing signals, particularly those that indicate the health status of the colony. Our approach allows us to analyze Fourier components from the continuous acquisition of sound from the comb. Two microphones are attached to each comb to record the sounds generated by the bees during a range of tasks. These sounds are fed via interfaces into a laptop. We hope that patterns and amplitudes of the Fourier components found reflect the typical division of work in a healthy colony and that an ongoing comparison over time will allow rapid detection of any abnormal division of work. A further goal of the study is to extract components of the Fourier analyses that indicate a massive threat to the colony, particularly as a result of pesticides being carried back to the hive by foraging bees.
By continuously monitoring and analyzing colonies at a number of local sites we are able to detect and register the introduction of harmful pesticides into the affected hives in a region.

Here we propose a new method with which environmental pollution can be detected on a temporally and spatially limited basis with the help of thousands of bees and which can be used as a basis for precise sampling as well as analysis. Using suitable detectors and programs we continuously and automatically evaluate the changes in cooperation and communication that occur in the bee colony as a result of the uptake of pesticides. Our work program relates to the intermediate phase following clarification of the basic suitability of the method (completed) and prior to larger scale implementation.

Environmental pollution occurrences are spatially and/or temporally distributed

Anthropogenic influences alter the natural environment. The effects on animals and plants, and thus directly and indirectly also on humans, are often not recognized or are extremely difficult to detect. The reason for this lies in the spatially limited and sometimes temporally transient changes, which additionally are often not accessible to the human senses. In the case of the application of pesticides in farming, the temporally and spatially limited effects are particularly blatant but they usually go undetected because the fungi, bacteria, insects and other smaller animals that are particularly sensitive to these pesticides easily escape our attention and the fact that the application of such pesticides is temporally and spatially limited means that chemical analyses frequently fail to provide any evidence of this. For practical and fiscal reasons too it is not possible to implement a chemical-physical monitoring of the environment with the necessary spatial and temporal resolution.
Now of course it is unavoidable that the particularly large number of pests that live off our agricultural products in our cultivated landscape of intensive farming and

monocultures must be controlled through the application of chemically or physically active methods. For reasons of cost, and frequently also from lack of knowledge, chemical methods are carelessly applied, the effects of which in turn usually remain unidentified. The result is that the need for a more a selective action of such pesticides can not be sufficiently represented by society. Unfortunately, this cycle of ignorance of the effects, lax handling, and the business interests of many participants has resulted in a situation where increased agricultural productivity is associated with a massive transformation of our environment, which also affects human health. Here, we need to strive for a turnaround that promotes the responsibility of all participants, and of society as a whole, so that the necessary information about the effects is made available, with the appropriate spatial and temporal resolution and at an acceptable financial cost. Here we propose a radical rethinking of environmental monitoring.

The effects of environmental pollution are dynamic, interconnected and combinatorial

Physical-chemical methods of recording environmental pollution are based on a monocausal understanding. Model organisms are examined to ascertain the dose at which approximately half of the organisms die (LD 60 dose). Even when an attempt is made to incorporate the complexity of the natural environment into the analysis, three principles will be considered insufficiently or not at all. (1) An LD 50 dose determination does not take into account that even at much lower doses the homeostatic regulating mechanisms of the organisms are affected, their sensitivity to other factors such as pathogens is impaired and long-term effects can occur that are not detected. (2) In the natural environment many factors work together in a combinatorial fashion. This network of effects is characterised by non-linear, abrupt transitions. (3) The temporal dynamic of these combinatorial effects is not taken into account in a mono-causal approach.
In ecology it is standard knowledge that a habitat is best characterized by the organisms living in it. Thereby it is primarily the so-called indicator organisms that characterize a habitat in its dynamic network of chemical, physical and biological factors. The reason for this is the fact that temporally limited factors as well as the combinatorial interweaving of such factors also significantly affect the living conditions of organisms in a habitat. The principle of environmental monitoring should therefore also ensure the cooperation and contribution of organisms in the habitat. The more comprehensive the information provided by the organisms and the more simply this information can be evaluated, the more effective this process will be.

Bees collect material and information

Bees live in social communities of 20,000 to 60,000 animals per colony, of which about half, respectively, are flying bees that collect not just food (nectar, pollen) but also material (water, resin) for their own colony. Along with the collected material information is also introduced into the bee colony in the sense that this material has a direct impact on the living conditions of the colony. Because bees have a complex system of communication mechanisms at their disposal the colony as a whole is in a position to strive for an optimal cost-benefit ratio. Much is already known about the flow of information behind the homeostatic interplay, other aspects are yet to be discovered. The

fact that many thousands of flying bees cover an area of 10 – 15 km^2, introducing information about this area into the colony along with the material collected is important in our context. The status of the colony is therefore directly dependent on the material introduced into the hive and will react to it. It is this reaction that provides us with information about the area. For this reason beekeepers move with their hives into habitats that offer particularly good sources of nectar. If a beekeeper finds that the nutritional status in a colony is one-sided he will try to take the hive to an area where this imbalance will be rectified. If the pollen and/or nectar is contaminated with pesticides e.g. as a result of pesticides being sprayed into the flower or if carried into the flower by wind, then the colony will react, in the worst case dying off (as has happened on a large scale in the USA as a result of the industrial application of pesticides and as has also occurred in Germany, e.g. in the Upper Rhein Valley). Such massive effects are immediately apparent to beekeepers; however sub-lethal damage, which mainly provides information about the status of the habitat, can often go unnoticed because it can be obscured by the manifold effects of other environmental factors. However, a very experienced beekeeper who simultaneously maintains colonies at a number of different locations may be in a position to register subtle changes by comparing the sites over time. Our aim is to record and evaluate the information that is assessed by the beekeeper in such a way that conclusions can be drawn about the status of the habitat and, in particular, its contamination.
Here we are not so much concerned with the bees and their well-being (although that too is an honourable aim), but with the detection of pollution that affects all other organisms, including humans. The disappearance of myriad solitary bees and wasps and many other organisms living in an area where the health status and survival of a colony of bees has been threatened by environmental pollution remains completely undetected, although this is the real problem. That human health is also affected, directly or indirectly, likewise remains hidden. Precisely as a result of their social colony structure and the large number of individuals, bees are the **ideal environmental police**.

A discovery: The social infrastructure of a colony of bees can be technically measured and recorded on an automatic and continuous basis. The parameters extracted in the process are indicators of the health status of the colony.

The social infrastructure of the bee colony is controlled and maintained by numerous forms of communication. Two sensory channels – the acoustic and the electrostatic - play a central role in this process. We discovered that the alternating electromagnetic fields that occur during movement of the highly insulated insect body are detected/picked up by the bees and represent social signals. Together with the acoustic and substrate vibratory signals, these electromagnetic signals represent highly sensitive indicators of the health status of the colony. We have developed methods that allow us to gain insights into the social infrastructure of the colony by analyzing the frequency spectra of these signals.
Acoustic channel: When bees build the wax cells of their combs, when they fill these cells with pollen and nectar, when they communicate using the waggle dance and other forms of acoustic signals, when they feed their larvae and when they make contact with the queen bee the resulting substrate vibrations are transferred to the wax cells and therefore to the entire hive. With the right microphones these vibrations can be recorded

and their frequency spectrum can be analyzed and attributed to specific hive activities. Based on this information it is possible to derive an acoustic finger print and to trace its development over time, its dependence on time of day or weather conditions and how it changes in response to external effects.

Electromagnetic signals: The insect body is composed of a highly insulating material (the cuticle is covered with wax). When the body parts rub against each other, as occurs mainly with movement of the wings and the abdomen, an electromagnetic charge results. Thus on arrival at the hive entrance flying bees carry charges that lead to voltage differences of several hundred volts. We were able to show that dancing bees are also charged by contractions of the flight musculature. Depending on the voltage, the electromagnetic fields expand up to several centimetres. We found that it is primarily the mechanoreceptors on and in the antennae that are responsible for the perception of these electromagnetic fields. Simple reconstruction of the capacitive microphones that we use to register the substrate vibrations allows us to measure the electromagnetic fields reliably. Here too an analysis of the frequency components and their development over time leads to a comprehensive characterization of the condition of the colony.

In a first paper, which is currently in the submission phase, we investigated the electromagnetic fields of the arriving flying bees, the reaction of the guard bees to their arrival, the generation and modulation of the fields during dance communication and the perception as well as the learning of these electromagnetic fields. It revealed that in bees the electromagnetic channel is an exceptionally rich communication channel that also reflects conditions in the colony as a whole in a highly sensitive manner. In the next section we present a brief summary of some of our most important findings.

Studies are currently underway in which the effects of pesticide pollution on acoustic and electrostatic signals in small bee colonies are being quantitatively recorded. With these studies we are also examining the predictive strength of the extracted frequency profiles and the temporal development of such “finger prints”.

Methodology for recording and evaluating acoustic and electrical signals in bee colonies

Here we present some of these finger prints for different situations, which characterize the validity of the method. The following three figures show the energy spectrum of the signals recorded with the acoustic and electrical microphones. The different types of activity form bell-shaped deflections of the Fourier spectrum around the main frequency. The harmonic frequency spectra are typical of hive activities at roughly the half, the double and multiples of the main frequency. The width and amplitude of the individual harmonic components reveal individual typical activity. Through continuous observation of the bees’ activities on the comb we identify the periods in which the different activities are dominant or appear alone.

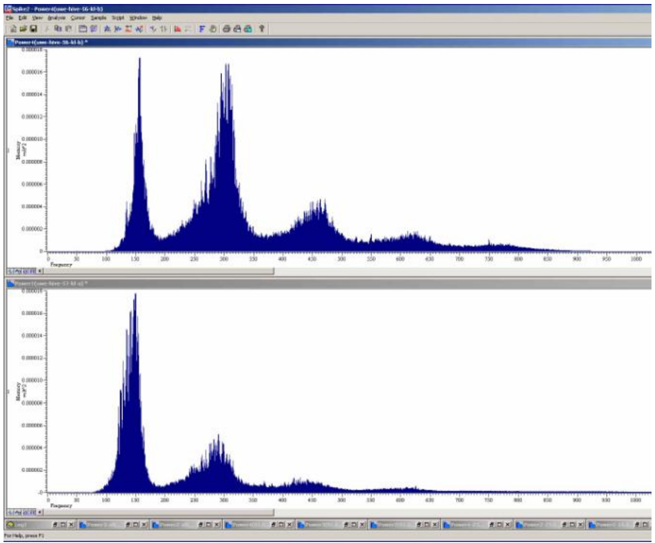


Figure 1 above: The energy spectrum of an observation hive with about 2,000 bees recorded at a time of high foraging activity in summer (11:30 to 13:00 hrs 18.07.2007). At approx. 300 Hz, the wing beats generated by the bees when thickening the nectar on the comb are particularly easy to identify.
Below: Between 15:20 and 16:15 hrs on the same day there was a significant decrease in foraging activity because the food sources set up by us had been emptied. There was a sharp drop in the energy of the main frequency at approx. 300 Hz and its harmonic components at 450 Hz, 600 Hz and 750 Hz. This indicates that these four components belong to the wing beat during thickening. The basic component at 150 Hz on the other hand increases and widens. Therefore it belongs to another activity that is connected to the thickening of the collected nectar and the temperature regulation.

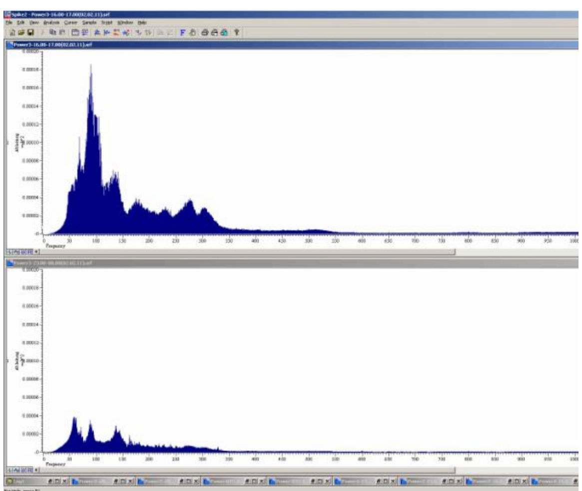


Figure 2 above: The energy spectrum in an observation hive with only 200 bees during the winter season without foraging activity. The activity was recorded on the comb from 16:00 to 17:00 hrs in January of this year. Here it is primarily the movement of the bees on the comb and the feeding of the larvae that is reflected.
Below: Here the night resting period from 23:00 to 24:00 hrs was recorded. This recording demonstrates the absolute sensitivity of the method.

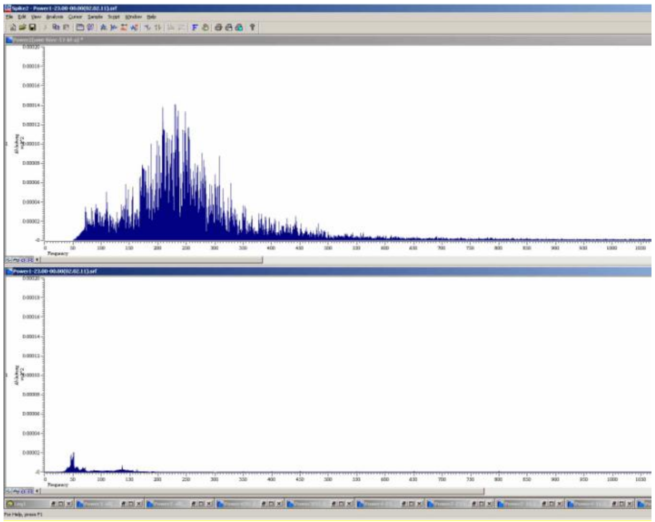


Figure 3 above: Wing movements during the waggle dance which were extracted by software from the total signal of the colony. The significant signal components lie in the range 230 to 280 Hz and are quite noisy due to the small wing movements. Below: Recordings from an empty hive located directly beside the observation hive serve as a control for our measurements. Very weak signals caused by background noise, e.g. traffic and footfall sounds, can be identified. These have no significant influence on our measurements.

Dance activity on the comb represents a special component of the work structure in a healthy, active hive. We pay particular attention to it because under otherwise favourable foraging conditions its absence indicates that the colony is under threat. Evidence that the dance rhythms are picked up by the dance-following bees and are thus part of social communication (Figure 4) is another important aspect for us.

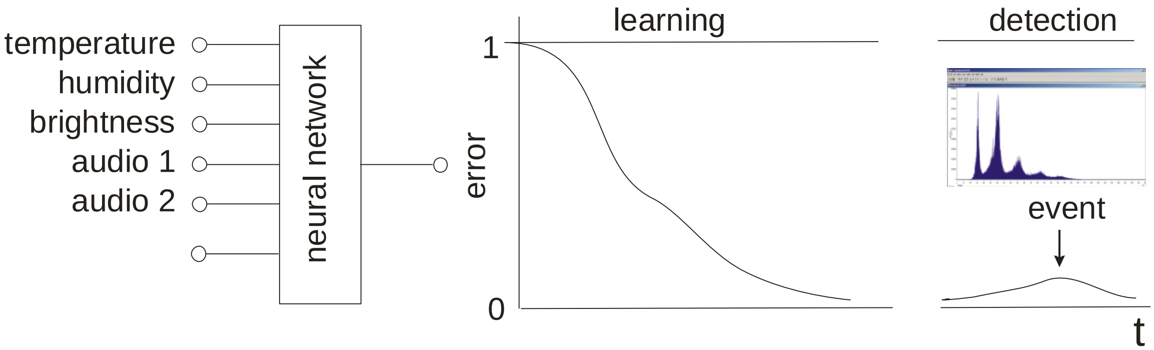
Figure 4: Example of a dance rhythm. This figure shows the pulse patterns generated by the wings that can be measured as alternating electromagnetic fields. The highly modulated part, here approx. 1 sec long, is the actual waggle run and encodes the distance to the feeding source. The breaks show the concentricity/circular run to the next starting position. The consecutive waggle runs are danced alternately rightwards and leftwards, following a figure-of-eight shape. The direction of the dance during waggling encodes the direction of the food source in relation to the position of the sun (not visible from the signal).

The characteristic properties of the electrical signals and the bees' perception of these were examined with a setup where single bee runs on the spot on a Styrofoam ball suspended in an air stream. This is illustrated in Figure 5. It was shown that the typical frequencies of the waggle dance (at 280 Hz) can be differentiated from those of the so-called beep tone (at 400 Hz).

0 min at rest 2sec dance rhythm 1 min later

Figure 5: Reactions of the antenna of a bee running on the spot on a Styrofoam ball.
The experimental animal is suspended by the thorax. Using its legs it is then in a position to move the light Styrofoam ball in all directions. After several hours of running on the spot on the ball the animals tire and then typically let their antennae hang down in parallel (first image on left). In this resting position we can test the animals' reactions to acoustic and electrical signals. If the electrical signal of a dance rhythm is emitted, e.g. for 2 sec, as an alternating electrical field by the front-right electrode then the bee will slightly raise the tips of its antennae according to the strength of the signal (centre image). Just one minute afterwards the antennae return to the resting position (right image). We localized the receptors for the electromagnetic signals in the sharply angled antenna joint (Johnston organ). By raising the tips of its antennae the bee attempts to localize the origin of the signal. The infra-red light-emitting diode (background left, in the centre image it is lit up) indicates the strength of the signal. This procedure can be repeated many times. If the signals are very strong the bees are roused and start to run.

Neural network for detecting abnormalities in the division of work in the colony.



Mode of action of the neural network for a single colony of bees: In the newly established colony the data from the various measuring devices are continuously fed into a neural network (software). During the learning phase the error output falls from a value of 1 (i.e. unknown) to a value of close to 0 (i.e. learned). Thereafter begins the detection phase, whereby the error output rises again temporarily in response to any newly occurring situation in the colony that was not previously learned. This event triggers a comparison of the current finger prints with the reference finger prints collected up to that point.

The findings from this comparison can be used to supplement traditional tests such as those carried out by beekeepers and, in addition, chemical analyses of material from the comb to detect the presence of harmful pesticides.