Using Information Theory Approach to study the Communication System and Numerical Competence in Ants

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Abstract

In order to study the communication and intelligence in social animals we have suggested a new approach based on ideas from Information Theory (Reznikova, Ryabko, 1990, 1996, Ryabko, Reznikova, 1996). A new set of experiments based on this approach is presented. The first idea is that in an efficient communication system the more frequet the use of a message the shorter its length. The second idea is that when using a complicated numerical system, one has to add and subtract small numbers, for example, when using Roman numerals, $VII = V + II, IX = X - I$, etc. In our experiments ants had to transmit information about the location of a "branch" situated on a long "trunk". Each branch ended in an empty trough, except for one filled with syrup.Food was placed on different branches with different frequencies.On pre-selected "special" branches a reward occured much more frequently than on the others. For example, in 1993 we chose two special branches 10 and 20 on which the food occured with a probability of 1/3 for each of them, while for any of the other 28 branches the probability was 1/84. When the ants had learnt this, they changed the way they transmitted the information about the coordinates of the branch containing food.The time required for transmitting a message "the trough with food is on the branch "$No10$" or "$No20$" by the ants considerably decreased, and so did the messages about branches in the vicinity of the special ones 10 and 20. Analysis of the data suggested that the ants used a method of "representing" integers analogous to the Roman numerals. The special numbers (10 and 20 in this case) played the same role as the special Roman numerals V, X, L etc. Thus, the ants seemed able to add and subtract small numbers.

1. Introduction

Many results of Information Theory may be considered as Nature laws and this has been realized immediately after appearance of the classic work of C. Shannon (1948). Further this science has been successively applied to problems in psychology and biology, for example, in the field of deciphering of genetic code, but as yet not extensively to problems of animal communication. The interest of scientists in the cognitive abilities of animals was initiated by C.Darwin (1859) who put forward the hypothesis that animals possessed some forms of behaviour which were evolutionary precursors of human thinking. Nowdays many researchers study the animal intelligence and "language behaviour" intensively, as one of the highest manifestation of rational activity. These investigations are of great importance not only for biology but also for cybernetics, psychology, linguistcs and for many of applied sciences including robotics. Impressive results concerning artificial intermediary languages, counting and number-related skills were obtained in primates, dolphins and the grey parrot (Gardner and Gardner,1969; Boysen and Berntson, 1989; Herman, 1986; Pepperberg, 1987 and others). One of the most complicated of the known natural "languages" in animals is the symbolic honeybee "Dance Language". Based on a distant homing system, discovered by K. von Frisch (1923) it was later intensively studied using different methods including use of a mechanical model (Michelsen, 1993).

Ants have to cope with a variety of tasks and some of them require rather complex communication. For example, in red-wood ant species, in order to obtain honeydew, a foraging group of $5 - 10$ ants have to find a

certain leaf with an aphid colony within such a huge 3-dimention space as a tree is for an ant (Reznikova and Novgorodova, 1998). A single "scout" first discovers the colony, and then must recruit her foraging group and communicate its location to them. Ants are known to use different communicative methods for recruitment: chemical trails, sound signals, kinopsis (reaction to the excited scout behaviour),tandems etc. (Holldobler and Wilson, 1990). But it remained unclear for a long time whether they have a distant homing system. In this context, a so-called tactile (or antennal) "code" has been discussed. A hypothesis regarding the existence of such an information transmission system in ants was put forward as early as 1899 by E. Wasmann. Up to now, however, attempts to decipher the ant 's antennal movements have not revealed any structural unity of signals and replies (Bonavita - Cougourdan and Morel, 1984; Lenoir and Jaisson, 1982).

As regards cognitive processes in social insects, excellent learning capacities are demonstrable in ants and bees. Some experiments have shown ants to be capable of abstraction, extrapolation and of other complicated tasks (Reznikova, 1982;Collet et al.,1993; Lehrer, 1996). But the bounds of their numerical competence have remained unclear. In honeybees, abilities amounting at least to protocounting have been demonstrated in experiments in which the isects had to use the number of landmarks as the criterion to find the feeder (Chittka et al., 1995).

Recently we have suggested a new approach to the study of ants "language" and intelligence, i.e., not to attempt to decipher the signals, but first to investigate just the process of information transmission. Our experiments based on information theory have shown that ants probably have an even more intricate form of communication than the honeybee and also a higher level of mental abilties (Reznikova and Ryabko, 1990, 1999). In our studies an ant scout has to transmit quantitative information to a foraging group and then the foragers have to find the food by themselves, without their scout. The experiments were so devised as to eliminate all possible ways for the ants to find the goal, except distant homing, i.e. an information contact with the scout. The time duration of the scout - foragers contact was measured.

The experiments are based on a fundamental fact of information theory. In an efficient communication system the frequency of use of a message and the length of that message are related. This relation is described by the equation $l = -\log p$, were l is the length of a message and p is its frequency of occurence. The informal pattern is quite simple: the more frequently a message is used in the language, the shorter is a word or a phrase coding it. For example, even in official documents, the words "White House" are used instead of "The Executive Branch of the Government of the United States of America". Professional slang, abbreviations etc. serve the same purpose. This phenomenon is manifest in all known human languages.

The second idea is that when using a complicated numerical system , one has to add and subtract small numbers. For example, when using the Roman figures $V + II, IX = X - I$, etc.

These ideas were tested in the following experiments. Ants were offered a "horizontal trunk" with 40 "branches" (see the general scheme in Fig.1).
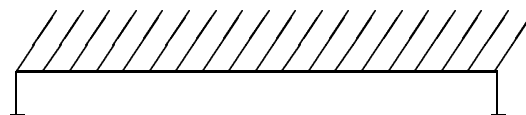

Fig. 1

Troughs with syrup were placed on different branches with different frequences. On the pre-selected two special branches (i.e. $No10$ and $No20$) food occured much more frequently than on the others (i.e. in 2 cases out of 3). When the ants had learnt this, they changed their way of transmitting the information about the branch containing food. The time required for transmission of a message "the trough with food is on the branch "$No10$" or "$No20$" by the ants was considerably reduced. This indicates that these insects have a communication system with a great degree of flexibility. In those cases when the trough with food was placed on branches close to the special ones (in our example - Nos. $11, 12, 9, 8, 21, 22, 19, 18$), the time required for transmitting the information about them by the ants also decreased considerably. Analysis suggests that the ants used a mode of "representing" numbers similar to the Roman numerals and the special numbers (10 and 20 in this case) seemed to play the same role as the special Roman numerals V, X, L etc. Our interpretation is that the ants can add and subtract small numbers. Before the opportunity to observe the skewed frequences,their starting code had message lengths proportional to N, suggestive of unary coding. Subsequent changes of code in response to special occurence- frequencies are in line with a basic information - theoretic principle.

2. Design of the experiments

The experiments were performed in 1992 - 1995, after a method had been improved in 1991. *Formica polyctena* was chosen as a group retrieving species with a high level of social organization. In various years 4 colonies of this species were used. Ants lived in a laboratory arena (200 x 200 cm), in a transparent nest (10 x 20 cm). The arena was divided into two sections: a smaller one, containing the nest, and a bigger one with an experimental system. Both sections were connected by a plastic bridge, that was from time to time removed to modify the setup or isolate the ants. The colonies consisted of about 2000

ants. All experimental ants were marked with colored labels and fed only in the experimental setup once every 2 - 3 days.

The experimental setup consisted of a long horizontal plastic "trunk" with 40 equally spaced plain plastic branches, of 6 cm length (although horizontal). Each branch ended in an empty trough, except for one filled with syrup. Ants came to the initial point of the trunk over an additional small bridge. The setup was mounted on glass props covered with slippery oil to prevent the ants from moving in a straight line.

As shown before (Reznikova and Ryabko, 1994),the foragers of this species separate into teams of $5-8$ specimens, each with one scout. As soon as the scout found food , it informed its foraging team. Using tweezers, we placed scouts on the branch with the trough containing food, and the scout returned to the nest on its own. Sometimes the scout contacted its team at once, and the group began moving towards the setup. In this case, after the scout contacted the foragers, we removed the scout and the foragers had to find the food by themselves. But more often, after the scout returned to the nest, it returned to the trough alone. Sometimes it made errors and only found the food-containing trough after visiting some empty ones. Then it returned to the nest again, contacted only one team, and either remained with the team or left it. In the first case the scout was isolated and we watched its foraging team. In the latter case we let the scout repeat its trips, sometimes up to four times, before it was able to mobilize the foragers.

In all the cases of mobilization , we measured the duration (in seconds) of the contact between the scout and the foragers together in the transparent nest. We considered the beginning of contact to occur when the scout touched the first forager ant, while we took the end of contact to be the moment when the nest was abandoned by the first two foragers. Contacts were followed by numerous antennal movements. Scouts touched one to four foragers in turn, sometimes two simultaneously. When the scout repeatedly returned to the trough alone, we measured the duration of each of its contacts with foragers. Only the duration of the last contact, followed by the foragers' abandonment of the nest, was taken into account. As a rule, all of the previous contacts were brief (1-5 sec.) and resulted only in food exchanges.

The experiments were so devised as to eliminate all possible ways helpful to finding the food , except distant homing, i.e. information contact with a scout. During contact between a scout and foragers in their nest, the experimental apparatus was replaced by a similar one with all troughs empty to avoid the use both of an odour track and air-borne food odour. So, following their contact with the scout, the foragers visited troughs that were purposely empty. When a compact forager group reached a goal, they were given a trough with syrup im-

Type of setup	Sample size	r	$a \pm \Delta a$	$b \pm \Delta b$
Vertical trunk 1	15	0.93	7.3 ± 4.1	-28.8 ± 0.51
Vertical trunk 2	16	0.99	5.88 ± 0.44	-17.11 ± 0.65
Horizontal trunk	30	0.91	8.54 ± 1.1	-22.2 ± 0.62
Circle	30	0.98	8.62 ± 0.52	-24.4 ± 0.61

Table 1: Values of correlation coefficient (r) and regression (a, b) coefficients

mediately, i.e. the trough at the goal was filled. The search was considered a success when the team came to the correct place leaving behind not more than 1 ant. An unseccessful search, when the team failed to come or came in a small number (more than 1 forager behind) was called a failure.

3. Ants' aptitude for transmitting information on the number of objects

The data on ants' capacity for counting and transmitting information on the number of objects were obtained in 1984-1987 and in 1992 and the results were partly published (Reznikova and Ryabko,1993,1996,1999). However, it is difficult to describe results of the new experiments dealing with ants' aptitude for simple arithmetical operations without mentioning the previous series. That is why we give here a brief description of these experiments.

The ants were offered a "trunk" with many branches and it was necessary to transmit the information about the number of the branch with syrup. In the recent experiments (next section) only a "horizontal trunk" with equally spaced branches of equal length was used, but when the ants' aptitude for counting was earlier studied we varied the distance between the branches as well as their length. To exclude the dependence of the duration of information transmission on the form of the setup or its spatial orientation, we performed experiments on the "vertical trunk" and on the circular setup.

In all cases the relation between the number of the branch i and the duration of the contact between the scout and the foragers t was linear, and may be described by the equality $t = ai + b$. The coefficient of correlation between t and i was high for different setups (Table 1).

The most parsimonious explanation is that ants can estimate the number of objects and transmit this information to each other. Presumably they may pass messages not about the number of the branch but about a distance to it or about the number of steps and so on. Even if it is so, this shows ants to be able to use quanti-

tative values and pass the information about them. But it is worthy of note that the relation between the number of the branch and the duration of the contact between the scout and the foragers is well described by the equality $t = ai + b$ for different setups which are characterized by different shapes , distances between branches and lengths of branches. The values of parameters a and b are close and do not depend either on the lengths of the branches nor on other parameters. All this enables us to suggest that ants transmit the information just about the number of the branch.

It is interesting, that quantitative characteristics of the ant's "number system" are close to some archaic human languages: the length of the code of a given number is proportional to its value. For example, "finger" corresponds to 1, "finger, finger" to the number 2, "finger, finger, finger" to the number 3 and so on. In modern human languages the length of the codeword of a number i is approximately proportional to $\log i$ (for large i's), and the decimal numeration system is a result of a long complicated development.

Note that when using the decimal numerical system, people have to make simple arythmetical operations: for example, $23 = 20+3$. It is particularly obvious in Roman numerals: for example, $VII = V + II$.

4.   Plasticity of the ants' "number system"

In the series here reviewed we examined the ants' aptitude to change the length of messages in correspondence with their frequency in ant's communication. The experiments were carried out in 1992-1995 on four *F. polyctena* colonies (data on 1992 are pilot-scale). A "horizontal trunk" with 40 branches was used, but we did not place the trough with syrup on branches $31-40$.

The experiment was divided into three stages. In each of them the regularity of placing the trough on branches with different numbers was changed. In the firs stages, in pre- selecting the number of the branch containing the trough, a table of random numbers was used (and once a certain number had been chosen, the trials with this number of the branch were repeated with $1-3$ different scouts). So the probability of the trough being on a particular branch was 1/30 because only branches $1-30$ were used. In the second stage we chose two special branches A and B ($No7$ and $No14$ in 1992, $No10$ and $No20$ in 1993, and $No10$ and $No19$ in 1994 - see also Table 2) on which the trough with syrup occured during the experiments much more frequently than on the rest - with a probability of 1/3 for "A" and "B", and 1/84 for each one of the other 28 branches. In this way, two messages - "the trough is on the branch A" and "the trough is on the branch B" - had a much higher probability of being required than the remaining 28 messages. In 1995 we used only one special point A (the branch $No15$). On

The number of the branch having food (experiments in different days, consiquently)	Distance to the nearest special branch	Times of transmission of information about the branch number for different scouts (sec.)
26	6	35,30
30	10	70,65
27	7	65,72
24	4	58,60,62
8	2	22,20,25
16	4	25, 28, 25
16	4	25
22	2	15,18
18	2	20,25,18,20
15	5	30,28,35,30
20	0	10,12,10
6	4	25,28
16	4	30,25
15	5	20,25,20
14	4	25,28,30,26
17	3	17,15
11	1	10,12

Table 2: Dependence of the time of information transmission (t) on the distance from the branch with a trough to the nearest special point (1993, special points are 10 and 20)

Sample size	Numbers of special branches	r for the first stage of the experiments	r for the third stage of the experiments
150	10,20	0.95	0.80
92	10,19	0.96	0.91
99	15	0.99	0.82

Table 3: Values of correlation coefficient (r) in the experiments with different "special" branches

this branch the food appeared with the probability 1/2, and 1/58 for each of the other 29 branches. In the third stage of the experiment, the number of the branch with the trough was chosen at random again.

Consider the relationship between the time which the ants spent transmitting the information about the branch containing food, and it's number. The data obtained at the first and third stages of the experiments are shown on the graphs in which the time of the scout's contact with foragers (t) is plotted against the number (i) of the branch with the trough. In the first stage the dependence is close to linear (the sample correlation coefficients characterizing the constraint force were equal to $0,95$ in 1993 and to $0,96$ in 1994, see also Table 3). At the third stage, the picture was different: firstly, the information transmission time was very much reduced,

and, secondly, the dependence of the information transmission time on the branch number is obviously non - linear: depression can be seen in the vivinities of the special points.

In 1995 the experimental scheme was the same but only one special point was used, namely the branch $No15$. In the first and the third stages of the experiment the food containing branches were chosen with equal probabilities $(1/30)$. In the second stage the trough appeared on the branch $No15$ with the probability $1/2$ versus $1/58$ for each of the other 29 branches. In the first stage time duration of information transmission about the food containing branch by ants was close to linear while in the third stage it sharply reduced,especially for the special branch $No15$ and the branches in its vicinity.

So, the data obtained demonstrate that the patterns of dependence of the information transmission time on the number of food - containing branch at the 1-st and 3-d stages of experiment are considerably different. It seems that the ants have changed the mode of presenting the data about the number of the branch containing food and rearranged their communication system. Moreover, in the vicinities of the special branches,the time of transmission of information about the number of the branch with the trough is, on the average, shorter when this branch is closer to the "special" ones.

For example, in 1993, at the first stage of the experiments the ants spent $70 - 82$ sec. to transmit the information about the fact that the trough with syrup is on the branch $No11$, and $8 - 12$ sec. to transmit the information about the branch $No1$. At the third stage it took $5 - 15$ sec. to transmit the information about the branch $No11$.

It should be noted that we were faced with some facts which could not be interpreted easily. Thus, in 1992 - 1994, in the second stage of the experiments, during $40 - 50$ trials (i.e. $12 - 15$ experimental days) the scouts spent for their contacts with foragers, in those cases when the trough was on the special branches, in average, the same time as at the first stage (for example, in 1994, it took from 62 to 80 sec. to transmit the information about the branch $No10$ (A), and from 100 to 120 sec. - about the branch $No19$ (B).

Then followed a period when the scouts, after visiting the special branches, devoted to the contacts with foragers strikingly prolonged time , such as 200 - 350 sec., and even up to 500 sec. After those contacts, a general mobilization of foragers was observed on the laboratory arenas, but only one team rushed to the bridge which led to the set-up. We did not observed such phenomena except in such periods of the experiments. These periods took 2 experimental days in 1992, 4 days in 1993 and 2 - in 1994. In 1995 we did not observed such a phenomenon and this may be connected with the fact that only 1 "special" branch was used).

5. Ants' ability to add and subtract small numbers

An analysis of the time duration of the information transmission by ants raises a the possibility that at the third stage of the experiment the messages of the scouts consisted of two parts: the information about which of the special branches is the nearest to the branch with the trough, and the information about the distance from this branch with the trough to this definite special branch. In other words, the ants are presumed to pass a "name" of the special branch nearest to the branch with the trough , and then the number which is necessary to add or subtract in order to find the branch with the trough.

In order to verify this statistically, let us calculate the coefficient of correlation between the time of transmission of information about the trough being on the branch i and the distance from i to the nearest special branch. For this purpose the data obtained at the 3rd stage of the experiment should be transformed to present them in a form shown in Table 2 where data of 1993 are given as an example. We excluded data concerning branches which are close to the start point of the set-up $(No1 - 4)$ because in these cases the ants have no need to add and subtract.

It can be seen from Table 3 that the coefficients of correlation between the transmission time and the distance to the nearest special point have quite high values and they differ significantly from zero (at the confidence level of 0.99). So the results support the hypothesis that the time of transmission of a message about the number of the branch is shorter when this branch is closer to any of the special ones. The high values of correlation coefficients show that the dependence is close to linear. This, in turn, suggests that at the third stage of the experiment the ants used a "number system" reminiscent of Roman numerals. On this hypothesis the numbers 10 and 20, 10 and 19 in different series of the experiments,played a role similar to that of the Roman numerals V and X. In 1995 the picture was the same. The number 15 was the special one. Thus, the ants were able to add and subtract small numbers.

Acknowledgements

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