THE USE OF IDEAS AND METHODS OF INFORMATION THEORY TO STUDY COMMUNICATION AND NUMERICAL COMPETENCE IN ANTS

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ABSTRACT

Here new possibilities are demonstrated that Information Theory offers to cognitive ethologists who study intelligence and language behaviour in animals. This is the first evidence of experimental studying of numerical competence in social animals using their own communicative means. Red wood ants (Formica polyctena) were shown to be able to grasp regularities, to use them for coding and "compression" of information, and to add and subtract small numbers to optimise their messages. Ethological aspects of these results have been described in the book "Animal Intelligence: From Individual to social cognition" by Reznikova [8]. In this paper the main ideas of Information Theory are presented that play a key role in the experimental paradigm. The first idea is that in an efficient communication system the more frequent 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, etc.

1. INTRODUCTION

Language behaviour and numerical competence are considered by cognitive ethologists the highest manifestations of animal cognition. There is some experimental evidence in literature that several advanced social species possess sophisticated communication systems, and they are able to reason about quantities and their relations. For instance, honey bees can efficiently translate the code in the "Dance Language" into flight to their destinations [3, 4, 7, 10]. The experiments of Chittka and Geiger [2] demonstrated that honey bees can use the number of landmarks as one of the criteria in searching for food sources. Chimpanzees have impressive "linguistic potential" revealed by means of intermediary languages in the course of language - training experiments [5,16]; detailed review in [8], and they successfully cope with tasks based on addition of items within sets of 10 ones [1]. Although it was intuitively clear that highly social animals are able to include simple "arithmetic" in their communication, until recent time, there were no experimental paradigms for direct examination of properties of animal language, and for studying numerical competence of animals basing on their natural communicative skills. Ants are good candidates for studying "reasonable" communication and cognition, because these insects are known to use a large variety of ways to attract their nest mates to a food source, and they can also switch between different methods of communication according to the situation (reviewed in [6,9]. However, methodological limitations have hampered the progress of studying "linguistic potential" of ants' communication and related cognitive skills. We have elaborated an experimental approach for studying ants' communication based on ideas of Information Theory [11, 12, 13, 14]. This approach has already allowed the demonstration of developed language and intelligence in some highly social ant species. The main point of this approach is that our experiments provide a situation in which ants have to transmit information quantitatively known to the experimentalists in order to obtain food. The information to be transferred by ants concerns a sequence of turns in the maze "binary tree" in one series of experiments, and the number of a branch in comb-like "counting mazes" in the other series. The use of ideas of Shannon entropy revealed the presence of potentially unlimited numbers of messages in ant "language". We also succeeded in studying some important properties of ant intelligence, namely, their abilities to memorize and use simple maze regularities, thus compressing the information to be transferred. The latter experiments were based on the ideas of Kolmogorov complexity [15]. Here we present the experimental paradigm for studying ants' "arithmetic" skills that in principle can be extended to other social animals possessing flexible behaviour and the need to pass and memories complex "messages". The paradigm is based on a fundamental idea of Information Theory which proposes that in "reasonable" communication system the frequency of the use of a certain message and the length of that message must correlate. This correlation is described by the equation $l = -\log p$, where l is the length of a message, and p is its frequency of occurrence. The informal pattern is quite simple: the more frequently a message is used in a language, the shorter is the word or the phrase coding it. Professional jargon, abbreviations, etc. serve the same pur-

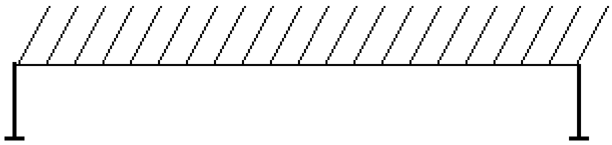

Figure 1. The counting maze: a horizontal trunk.

pose. This phenomenon is manifested 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 Roman numerals, VII = V + II, IX = X-I, etc.

2. DESIGN OF THE EXPERIMENTS

The main methodological idea is that we can judge how ants represent numbers by estimating how much time they spend on "pronouncing" numbers, that is, on transferring information about numbers of objects. In our experiments ants had to transmit information about the location of a "branch" situated on a long "trunk" (Fig. 1). Each branch ended in an empty trough, except for one, filled with syrup. In various years four colonies of red wood ants (F. polyctena) were used in this set of experiments. Ants lived in the 2 x1.5m laboratory arena, in a transparent nest that made it possible for their activity to be observed. The arena was divided into two sections: a smaller one containing the nest, and a bigger one with an experimental system. The two sections were connected by a plastic bridge that was removed from time to time to modify the set-up or isolate the ants. The laboratory colonies consisted of about 2000 specimens each. All actively foraging ants were individually marked with colored paint. Ants were required to transfer to foragers in a laboratory nest the information about which branch of a special "counting maze" they had to go to in order to obtain syrup. "Counting maze" is a collective name for several variants of set-ups. All of them serve to examine how ants transfer information about number of objects. The first variant of the counting maze is a comb-like set-up consisting of a long horizontal plastic trunk with 25 to 60 equally spaced plain plastic branches, each of them 6 cm in length. Each branch ended with an empty trough, except for one filled with syrup.

The second variant is a set-up with vertically aligned branches. In order to test whether the time of transmission of information about the number of the branch depends on its length as well as on the distance between the branches, one set of experiments was carried out on a similar vertical trunk in which the distance between the branches was twice as large, and the branches themselves were three times and five times longer (for different series of trials). The third variant was a circular trunk with 25 cm long branches. In all cases the set-ups were mounted on glass props covered with slippery oil to prevent the ants from moving in a straight line. Ants came to the initial point of the trunk over a small bridge. As shown before [12] the foragers of this species separate into teams of 4-8 specimens, each with one scout. As soon as the scout found food, it informed its own foraging team. In the course of experiments, we placed scouts one by one 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 to move towards the set - up. In this case, after the scout contacted the foragers it was removed for a while, and the foragers had to search for the food by themselves, without their guide. But more often the scout turned to go back to the trough alone. Sometimes it made errors and found the trough containing food only after visiting some empty ones. Then it returned to the nest again and contacted its team. Sometimes the scout had to make up to four trips before it could mobilize the foragers. In all cases of mobilization the duration of the contact between the scout and the foragers was measured in seconds. The contact was considered to begin when the scout touched the first forager ant, and to end when the first two foragers left the nest for the maze. When the scout repeatedly returned to the trough alone, each of its contacts with foragers was measured. Only the duration of the contact that was followed by the foragers' abandonment of the nest was taken into account. These contacts were hypothesized as "informative", and they sharply differed from other contacts by duration: all were more than 30 seconds. As a rule, all of the previous contacts between scouts and foragers were brief (about 5 seconds) and were aimed at food exchanges. All experiments were devised so as to eliminate all possible ways that could help the ants to find the food, except information contact with the scout. To avoid the use of an odour track, the experimental set-up was replaced by an identical one when the scout was in the nest or on the arena contacting its group. The fresh maze contained all troughs filled with water to avoid the possible influence of the smell of syrup. If the group reached the correct branch, they were immediately presented with the food. The search was considered a success when the team came to the correct place leaving behind not more than one ant. An unsuccessful search, when the team failed to come or came in a small number (more than one forager behind) was called a failure.

3. ANTS' CAPACITY FOR TRANSMITTING INFORMATION ON THE NUMBER OF OBJECTS

In the first series of experiments the findings concerning number-related skills in ants were based on comparisons of duration of scout - foragers information contacts which preceded successful trips by the foraging teams. Scouts were required to transfer to foragers in a laboratory nest the information about which branch of a "counting maze" they had to go to in order to obtain syrup. In total, 32 scout - foragers teams worked in three kinds of set-ups. The teams abandoned the nests after they were contacted by scouts and moved towards the trough by themselves 152 times (recall that the scouts were removed). In 117 cases the team immediately found the correct path to the trough, without making any wrong trips to empty troughs. In the remaining cases, ants came to the empty troughs, and began looking for food by checking neighbouring branches. Some scouts were experimentally found to be incapable of this task: in all experiments (31 in total) involving them the foragers failed to find the food. Such scouts were further removed from the working part of the arena. Since all set-ups had no fewer than 25 branches, the probability of finding the correct trough by chance is not more than 1/25. Thus, the success ratio which was obtained experimentally can only be explained by information transmission from the scouts. The probability of finding the food-containing trough by chance in 117 cases out of 152 is less than 10^{-10}. In addition, in control experiments ants, including scouts placed in the set-up, without having information on which trough contained food usually failed to find the food, even though they actively searched for it. It turned out 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 set-ups which are characterised by different shapes, distances between the branches and lengths of the branches. The values of parameters a and b are close and do not depend either on the lengths of the branches or on other parameters. The correlation coefficient between t and i was high for different kinds of counting mazes (Table 1). All this enables us to suggest that the ants transmit information solely concerning the number of the branch. The likely explanation of the results concerning ants' ability to search the "right" branch is that they can evaluate the number of a branch in the sequence of branches in the maze and transmit this information to each other. As it has been already noted before, foragers in the nest were absolutely uninformed about the location of the reward in the maze, and, taking into account that the set-up was replaced with a new one lacking both possible ants' odour trails and the smell of syrup, they could only obtain this information from an experienced scout. Presumably a scout could pass messages not about the number of the branch but about a distance to it or about the number of steps and so on. What is important is that even if ants operate with distance or with the number of steps, this shows that they are able to use quantitative values and pass on information about them. It is interesting that quantitative characteristics of the ant's "number system" seem to be close, at least outwardly, to some archaic human languages: the length of the code of a given number is proportional to its value. For example, the word "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 code word of a number i is approximately proportional to $\log i$ (for large i's), and the modern numeration system is a result of a long complicated development. Note that when using our numerical system, people have to make simple arithmetical operations: for example, 23 = 20 + 3. It is particularly obvious in Roman numerals: for example, VII = V + II.

Table 1. Values of correlation coefficient (r) and regression (a, b) coefficients for vertical trunk (vert), horizontal trunk (horiz), and circle in the experiments with F. polyctena

Type of setup	Sample size	Nr of Branches	r	a	b
Vert.1	15	40	0.93	7.3	-28.9
Vert.2	16	60	0.99	5.88	-17.11
Horiz.1	30	25	0.91	8.54	-22.2
Horiz.2	21	25	0.88	4.92	-18.94
Circle	38	25	0.98	8.62	-24.4

4. ANTS' ABILITY TO ADD AND SUBTRACT SMALL NUMBERS

The second series of experiments enabled us to suggest that ants are capable of simple arithmetic operations. A new experimental scheme was elaborated for studying ants' "arithmetic" skills based on a fundamental idea of information theory, which is that in a "reasonable" communication system the frequency of usage of a message and its length must correlate. The main experimental procedure was similar with other experiments with counting mazes. In various years four colonies of F. polyctena were used in this set of experiments. The scheme of the experiments was as follows. Ants were offered a horizontal trunk with 30 branches. The experiments were divided into three stages, and at each of them the regularity of placing the trough on branches with different numbers was changed. At the first stage, the branch containing the trough with syrup was selected randomly, with equal probabilities for all branches. So the probability of the trough with syrup being placed on a particular branch was 1/30. At the second stage we chose two "special" branches A and B (N 7 and N 14; N 10 and N 20; and N 10 and N 19 in different years) on which the trough with syrup occurred 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 of the other 28 branches. In this way, two "messages" - "The trough is on branch A" and "The trough is on branch B" - had a much higher probability than the remaining 28 messages. In one series of trials we used only one "special" point A (the branch N 15). On this branch the food appeared with the probability of 1/2, and 1/ 58 for the other 29 branches. At the third stage of the experiment, the number of the branch with the trough was chosen at random again. Now let us consider the relationship between the time which the ants spent to transmit the information about the branch containing food, and its number. The data obtained at the first and third stages of the experiments are shown on the graph (Fig. 2) in which the time of the scout's contact with foragers (t) is plotted against the number (i) of the branch with the trough. At the first stage the dependence is close to linear. At the third stage, the picture was different: first, the information transmission time was very much reduced, and, second, the dependence of the information transmission time on the branch number is obviously non-linear: depression can be seen in the vicinities of the "special" points (10 and 20). So the data demonstrate that the patterns of depen-

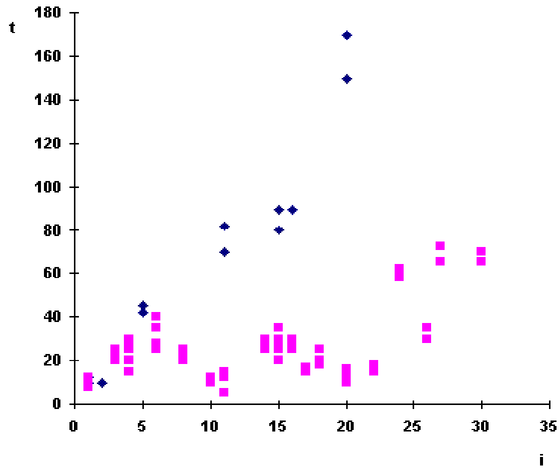

Figure 2. Dependence of the time (t; measured in seconds) of transmission of information about the number of the branch having food on its ordinal number (i) in the first and the third series of experiments in the ant Formica polyctena. Diamonds, the time taken for transmission of information at the first stage; Squares, the same it the third stage.

dence of the information transmission time on the number of the food-containing branch at the first and third stages of experiments are considerably different. Moreover, in the vicinities of the "special" branches, the time taken for transmission of the information about the number of the branch with the trough is, on the average, shorter. For example, in the first series, at the first stage of the experiments the ants took 70- 82 seconds to transmit the information about the fact that the trough with syrup was on branch N 11, and 8-12 seconds to transmit the information about branch N 1. At the third stage it took 5-15 seconds to transmit the information about branch N 11. These data enable us to suggest that the ants have changed the mode of presenting the data about the number of the branch containing food.

What about ants' ability to add and subtract small numbers? Analysis of the time duration of the information transmission by ants raises 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 was the nearest to the branch with the trough, and the information about the distance from the branch with the trough to this definite "special" branch. In other words, the ants, presumably, passed a "name" of the "special" branch nearest to the branch with the trough, and then the number which had to be added or subtracted in order to find the branch with the trough. In order to verify this statistically, the coefficient of correlation was calculated 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. The results confirmed 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. For this purpose, the data obtained at the third stage of the experiment were transformed to present them in the form shown in Table 2 where data of one year are given as an example. In this table we do not include branches that are close to the starting point of the set-up (N 1-4) because there is no need to use "arithmetic" for ants where rewarded branches are very close to the first one (in fact ants spent roughly the same time transmitting information about these branches: from 10 to 20 seconds).

Table 2. Dependence of the time of information transmission (t) on the distance from the branch with a trough to the nearest "special" branch (special branches are 10 and 20)

The number of the branch having food (experiments in different days, consequently)	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	25,8,25
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

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

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

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

time of transmission of a message about the number of the branch is shorter when this branch is close to either of the special ones. This, in turn, shows that at the third stage of the experiment the ants used simple additions and subtractions, achieving economy in a manner reminiscent of the Roman numeral system when the numbers 10 and 20, 10 and 19 in different series of the experiments, played a role similar to that of the Roman numbers V and X. Our interpretation is that ants of the considered species can add and subtract small numbers. This also indicates that these insects have a communication system with a great degree of flexibility. Until the frequencies with which the food was placed on different branches started exhibiting regularities, the ants were "encoding" each number of a branch with a message of length proportional to i, which suggests of unitary coding. Subsequent changes of code in response to special regularities in the frequencies are in line with a basic information-theoretic principle that in an efficient communication system the frequency of use of a message and the length of that message are related.

5. ACKNOWLEDGMENTS

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Reference

[1] M. J. Beran, *"Long-term retention of the differential values of Arabic numerals by chimpanzees (Pan troglodytes)",* Animal Cognition, v.7, pp.86-92, 2004.

[2] L. Chittka and K. Geiger, *"Can honeybees count landmarks?"*, Animal Behaviour, v. 49, pp.159-164, 1995.

[3] K. von. Frisch, *"Uber die Sprache der Bienen. Zoologische Iahrbucher,"* Abteilung fur Allgemeine Zoologie und Physiologie der Tiere, v.40, pp. 1-119, 1923.

[4] K. von Frisch, *The dance language and orientation of bees,* Harvard Univ. Press, Cambridge, Massachusetts, 1967.

[5] R. A. Gardner and B. T. Gardner, *"Teaching sign language to a chimpanzee,"* Science, v.165, pp. 664-672, 1969.

[6] B. Holldobler and E. O. Wilson, *The ants,* Cambridge, The Belknap Press of Harward University Press, 1990.

[7] A. Michelsen, *"The transfer of information in the dance language of honeybees: progress and problems,"* Journal of Comparative Physiolology, A, Sensory, Neural and Behavioural Physiology, v. 173, pp. 135-141, 1993.

[8] Zh. Reznikova, *Animal Intelligence: From individual to social cognition,* Cambridge University Press, Cambridge, 2007.

[9] Zh. Reznikova, *"Dialog with black box: using Information Theory to study animal language behaviour",* Acta ethologica, v. 10, pp. 1-12, 2007.

[10] J. R. Riley, U. Greggers, A. D. Smith, D. R. Reynolds and R. Menzel, *"The flight paths of honeybees recruited by the waggle dance",* // Nature, v. 435, pp. 205-207, 2005.

[11] Zh. I. Reznikova, B. Ya. Ryabko, *"Investigations of ant language by methods of Information Theory,"* Problems of Information Theory, v. 21, n. 3, pp.103-108, 1986.

[12] Zh. I. Reznikova, B. Ya. Ryabko, *"Experimental study of the ants communication system with the application of the Information Theory approach,"* Memorabilia Zoologica, v. 48, pp. 219-236, 1994.

[13] Zh. I. Reznikova, B. Ya. Ryabko, *"In the shadow of the binary tree: Of ants and bits"*, In: Proceedings of the 2nd Internat. Workshop of the Mathematics and Algorithms of Social Insects, ed. C. Anderson and T. Balch. Atlanta, Georgian Institute of Technology, pp. 139-145, 2003.

[14] B. Ya. Ryabko, *"Methods of analysis of animal communication systems based on the information theory",* In: Sensory Systems of Arthropods, ed. K. Wiese, F. G. Gribakin, A. V. Popov and G. Renninger. Basel, Birkhauser, Verlag, pp.627-634, 1993.

[15] B. Ya. Ryabko, Zh. I. Reznikova, *"Using Shannon Entropy and Kolmogorov Complexity to study the communicative system and cognitive capacities in ants"*, Complexity, v.2, pp. 37-42, 1996.

[16] E. S. Savage-Rumbaugh, *Ape language: From conditioned response to symbol*, New York: Columbia University Press, 1986.