Using Shannon Entropy and Kolmogorov Complexity To Study the Communicative System and Cognitive Capacities in Ants

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INTRODUCTION

The communication systems of animals as well as their cognitive abilities have been a matter of special research interest to biologists, psychologists, linguists, and many others including investigators in the field of robototechnique. During the last three decades, quite new experimental approaches, including those based on a direct dialog with animals taught artificial intermediary languages, have been developed [1–4]. It has become possible to demonstrate that primates are capable not only of decision-making, generalization and extrapolation operations, but also of using very simple grammatical rules and such visual symbols as lexigrams, letters and numbers [5, 6]. Counting and number-related skills have been demonstrated in the grey parrot [7]. It has been believed for a very long time that cognitive activity is only possible in vertebrates; however, Mazokhin-Porshnyakov's experiments [8, 9] have demonstrated that honeybees and social wasps are capable of abstraction, extrapolation, and of solving rather complicated tasks.

The question of the existence of a developed natural language in some social animal species remains obscure. The most complicated of the known natural "languages" in animals is the symbolic honeybee "dance" based on a distant homing system. This intricate form of communication was discovered by K. von Frisch [10] and then was intensively studied using different methods [11, 12].

The signal activity of ants has also attracted the attention of many researchers. Ants are known to be able to use a large variety of communication means for attraction to a food source [13]. It has remained unclear for a long time whether they have a distant homing system. In this aspect, the so-called tactile (or antennal) "code" has been actively discussed. A hypothesis regarding the existence of such an information transmission system in ants was put forward as early as 1899 by E. Wasmann [14]. However, the numerous attempts to decipher ant "language" have not given the desired results [15, 16]. Ants' capacity for solving logical problems and for transmiting complicated information by means of a distant homing system has been demonstrated by Reznikova [17–19]. But nothing about language-related skills was known.

The main difficulties in the analysis of animal language appear to be methodological. Many workers have tried to decode

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animal languages by looking for "letters" and "words" and by compiling "dictionaries." With such an approach, it often remains unclear which sounds and gestures have something to do with the language and which have not, and there are also some technical difficulties connected with the high mobility of animals and often with their inaccessibility for recording signals. The fact that scientists have managed to compile dictionaries only for the honeybee appears to indicate not that other animals lack language, but that adequate methods are lacking.

At the end of the 1940s, C. Shannon developed the basis of Information Theory [20]. The fundamental role of this theory was appreciated immediately, not only in the development of the technology of information transmission, but also in the study of natural communication systems. It is natural to use information theory in the investigation of communication systems because this theory presents general principles and methods for developing effective and reliable communication systems. In particular, in the 1950s and 1960s the entropies (degree of uncertainty and diversity) of most European languages was estimated. Later, information theoretical ideas entered the field of physiology. For example, human reaction time under experimental conditions turned out to be

FIGURE 1

The maze "binary tree" with one fork (a) and four forks (b).

proportional to the uncertainty present in the experiment [21]. Surprisingly, applications of information theory have been incorporated in only a few studies. Thus, information theory was used to estimate the quantitative parameters of the honeybee's ability to memorize the location of a food source [22].

We describe quite a different approach to the study of animal communication and cognition based on the ideas of Shannon entropy and Kolmogorov complexity. This approach has already allowed the demonstration of developed language and intelligence in some high social ant species. The main results have been published in biological journals [23–25] and announced and discussed in international conference prodeedings [26–29].

The main point of this approach is that our experiments provide a situation in which ants have to transmit information quantitatively known to the experimentalist in order to obtain food. This information concerns the sequence of turns toward a trough of syrup. We used the new laboratory setup called "binary tree" where each "leaf" of the tree ends with an empty trough with the exception of one filled with syrup. The simplest design was the tree with two leaves and two troughs, with syrup in only one of them [Figure 1(a)]. In this situation an ant scout should transmit one bit of information to foragers: to go to the right or to the left. In other experiments the number of forks in one branch increased to six [Figure 1(b) shows a setup with four forks]. Hence, the number of bits necessary to choose the correct way is equal to the number of forks. The sequence of turns was randomly taken by tossing a coin. The setup was made of plastic sticks (50 mm) and balls (10 mm). To prevent access to food in a straight line, the setup was placed in a water bath (600 x 600 mm). The ants reached the initial point of the tree going over a bridge (Figure 2).

The use of the ideas of Shannon Entropy allowed the presence of potentially unlimited numbers of messages in ant "language" to be demonstrated and estimates of the rate of the information transmission (approximately 1 bit/min.) to be made. We also succeeded in studying some properties of ant intelligence, namely, their ability to memorize and use simple regularities, thus compressing the information available. The latter experiments were based on the ideas of Kolmogorov complexity. We believe that the experimental schemes described can be used to study the communication systems of other animals.

DESCRIPTION OF EXPERIMENTS

The experiments were performed since 1982 on three species of ants, each with a high level of social organization. Ants lived in the 2 x 2 m laboratory arena, in a transparent nest. The colonies consisted of 800–2000 specimens. All experimental ants were marked with colored labels and fed once every three days—only in the experimental setup.

In all series of the experiments with the binary tree, the ants fed for 10–12 days in the one-fork setup. In these cases
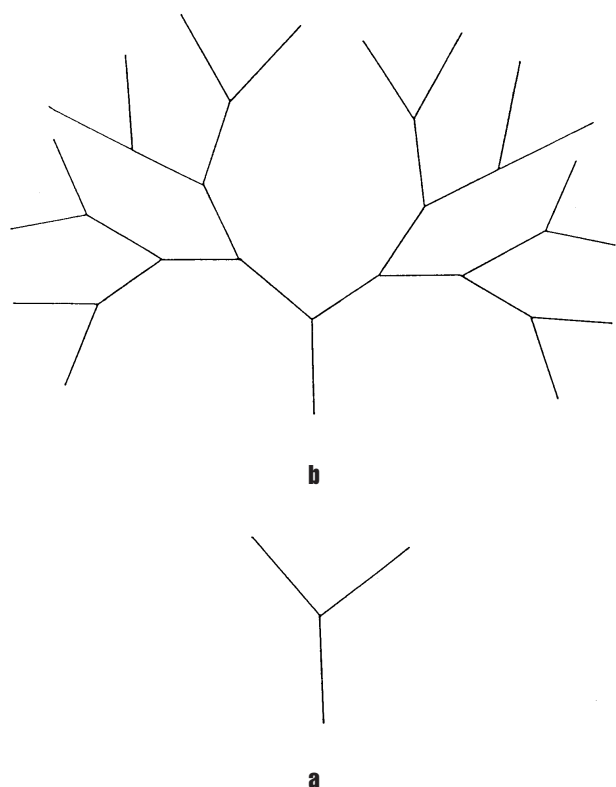
the foragers left their nest as a result of collective excitement and imitation. The ants' behavior changed sharply when the trough with syrup was placed on one of four leaves of the second turn of the binary tree, making their task more complicated.

The laboratory colony included "teams" which had one scout and five to eight recruits: the scout attracted only its team to the food. The teams were revealed in special preliminary experiments. Not all of the scouts managed to memorize the way toward the maze; moreover, the number of such scouts dropped with the complication of the task, e.g., in the case of two forks all active scouts and their groups were working, while in the case of six forks, only one or two were working. In total, more than 200 teams of three ant species were used in our experiments.

During the experiments we placed scouts on 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 toward the setup. In this case, after the scout contacted the foragers, we isolated the scout and the foragers had to search for the food by themselves. But more often, after the scout returned to the nest, it left and returned to the trough alone. Sometimes it made errors and found the food-containing trough only after visiting some empty ones. Then it returned to the nest again, contacted the team and either remained with the team or left it. In the first case, the scout was isolated, while in the second case, we performed the experiment repeatedly. Sometimes the scout had to make up to four trips before it could mobilize the foragers. In all cases of mobilization we measured the duration (in seconds) of the contact between the scout and foragers in the 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 often by numerous antennal movements. Scouts contacted one to four foragers in turn, sometimes two simultaneously. When the scout repeatedly returned to the trough alone, we measured 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 previous contacts were brief (1–5 sec.) and destined for food exchanges.

During each series of experiments with the trough placed on the ith leaf of the binary tree, all forager groups that were active on that day (one to five) worked successively. While the trial was going on, we took away the bridge leading to the working part of the arena so as not to let members of other groups go there.

The experiments were devised to eliminate all possible ways helpful to finding food, except distant homing, i.e., information contact with a scout ant. During contact between a scout and foragers in their nest, the experimental setup was replaced by a similar one to avoid the use of an odor track. To

FIGURE 2
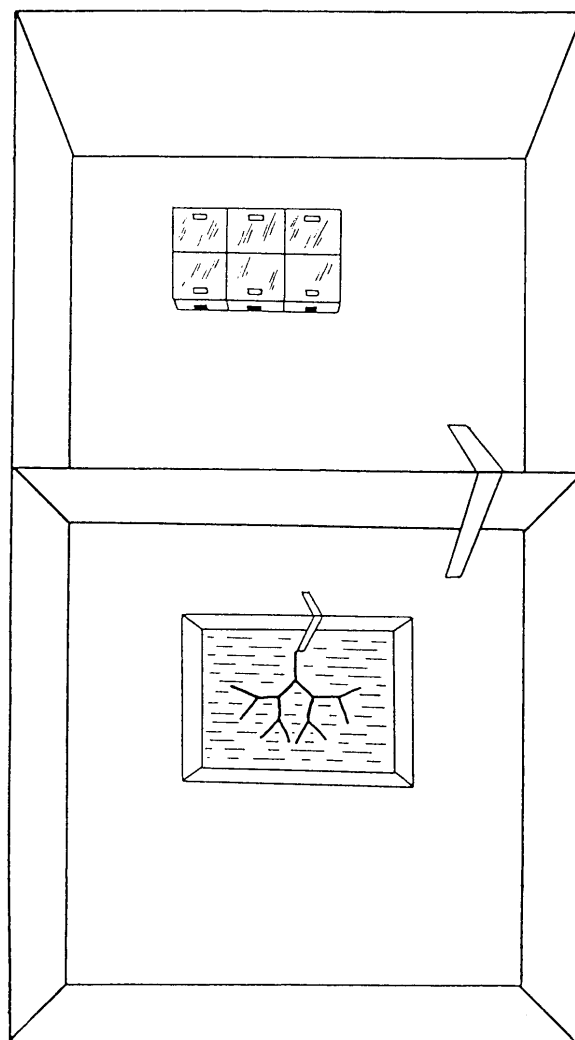
The laboratory arena with the maze "binary tree."

avoid both the trail and the food odor a special series of experiments was carried out. While the scout was inside the nest, we replaced the whole maze by a new one with all troughs empty. So, following their contact with the scout, the foragers visited troughs empty on purpose. Such experiments were called "examinations." Ants were fed during the intervals between those examinations, but they had no food during any particular examination.

Shannon Entropy and Information Transmission in Ants

In our experiments the groups of foragers, after a contact with the scout, in most cases found the bait faultlessly. Table 1 gives the results of the examinations, during which ants visited the maze after empty troughs had been placed there. We shall first prove the existence of information transmission in ants. We compare Zero Hypothesis H_0 (foragers occasionally find a

No	Scout	Sequences of the turns	The compact group of foragers achieved the aim following their contact with the scout	The same whith 1-3 being back	forages failed to achieve the aim
			Results		
1	I	RRR	+		
2	II	LRR			+
3	II	LRR			+
4	III	RRR			+
5	III	RLR	+		
6	III	RRL	+		
7	III	RLL	+		
8	IV	LRL	+	+	
9	IV	RLL	+	+	
10	V	RLL	+	+	
11	VI	LRL	+		
12	VI	LRL	+	+	
13	VI	LLR	+		
14	VII	LRR	+		
15	VII	LLL	+		
16	VII	RLL	+		
17	VIII	LLL	+		
18	VIII	LRL	+		
19	IX	LLR	+	+	
20	IX	RLL	+		

Results of the Formica sanguinea "exams"

Species	$a \pm \Delta$	$b \pm \Delta$	r
F. sanguinea	0.738 ± 0.053	-0.768 ± 0.094	0.962
F. polyctena	1.094 ± 0.050	0.619 ± 0.460	0.791
C. saxatilis	1.189 ± 0.018	0.334 ± 0.032	0.967

The Parameters of linear regression and sample correlation coefficient

turns, they usually failed to find the food during this period. Such ants, checking the way toward their nest, often returned to the bridge and began searching again. Note, that during all experiments scouts were specially introduced into the maze because their leaf-checking to find the food was usually unsuccesful.

The quantity of information (in bits), necessary for choosing the correct way toward the maze, equals i, the number of forks. We assumed that the duration of the contacts between the scouts and foragers (t) was $ai + b$, where i is the number of forks, a-coefficient of proportionality, equal the rate of the information transmission (bit/min), and b was the introduced constant, since ants can transmit information not related directly to the task, for example the simple signal "food." Besides, it is not ruled out that a discovering ant transmits, in some way, the information on its route to the nest, using acoustic or some other means of communication. For us, it is important that the way from the maze to the nest was in all experiments approximately the same and, therefore, the time before the antennal contact with the foragers in the nest, which the scout could hypothetically use for the message transmission, was approximately the same and did not depend on the number of forks.

trough) with Hypothesis H_1 (they find food thanks to the received information). The probability of a chance finding of the correct way toward the trough in the maze with three forks is $(1/2)^3$. Table 1 shows that in three cases (lines 2,3,4) the groups of foragers failed to find the food; in five cases (lines 8,9,10,12,19) one to three ants were left behind the group, and in 12 cases all foragers correctly reached those leaves where their scout had found food. In these experiments a correct search can be considered a success, while an unsuccessful search, when the team failed to come or came in a small number was called a failure.

Thus, we have results of 20 independent Bernoulli tests, where the probability of success (P) in the case of the realization of H_0 is $(1/2)^3$, against H_1, where P > 1/8. There were 12 successes and eight failures. To verify H_0 against H_1, we used the binomial criterion (see the tables in [30]). In our case H_0 was rejected in favor of H_1, P < 0.001. Thus, the obtained data showed that the ants had not used any trail or food odor (note that we had changed the maze and the troughs were empty). In addition, this table shows the scouts' ability to transmit information on absolutely different routes toward the bait during one experiment (e.g., lines 9–10 ,11–13, 14–16, etc.). So, the ants could not use the earlier experience.

Apart from the statistical analysis of the number of faultless findings of the goal by a group, we carried out control experiments in which ants were specially introduced into the maze, without contacts with a scout. They were permitted to search for food for 30 minutes. If the maze had three or more

From the obtained data, we evaluated the parameters of linear regression and the sample correlation coefficient (r) (Table 2). In all cases the correlation between the duration of the contacts and the amount of information (the numbers of the forks i) turned out to be close to linear, probably because of the high value of the sample correlation coefficient (Table 2). All values of correlation coefficient significantly differ from 0 at P = 0.01.

In three ant species the rate of the information transmission (a) derived from the equation $t = ai + b$ is 0,738, 1,094, and 1.189 bit/min., respectively. We do not consider these values as species constants; they probably vary. It is noteworthy that these values are, by about an order, smaller than that of human communication [21].

Let us now count the total number of different possible ways to the trough. In a simplest binary tree with one fork there are two leaves and therefore two different ways. In a tree with two forks there are 2^2 ways, with three forks, 2^3 ways, and with six forks, 2^6 ways; hence, the total number of different ways is equal to $2 + 2^2 + 2^3 + \ldots + 2^6 = 126$. This is the minimal number

of messages the ants must possess in order to solve the given task using the distant homing system.

Kolmogorov Complexity and Ants' Intelligence

The ability to quickly grasp the regularities and use them for coding and "compression" of information should be considered one of the most important properties of language and its carrier's intellect. Thus the length of the text should be proportional to the complexity of the information. This idea is a basic concept of Kolmogorov complexity. This concept is applied to words (or text), composed of the letters of the alphabet, for example, of an alphabet, consisting of two letters, e.g., L and R.

Informally, the complexity of a word (and its uncertainty) equals the length of its most concise description, according to Kolmogorov. For example, the word "LLLLLLLL" can be represented as "8L," the word "LRLRLRLR" as "4 LR," while the "random" word of shorter length "LRRLRL" probably cannot be expressed more concisely. Thus, the first word is the simplest one with the least uncertainty, the second is more complex, and the third one is the most complex and has the greatest uncertainty. We tried to analyze the question of whether ants can apply simple "text" regularities for compression (here the "text" means the sequence of the turns toward the maze).

As proven by Kolmogorov [31], there is no algorithmically evaluated quantitative measure of text complication. So, strictly speaking, we can only verify whether ants and humans have the same notion of simple and complex texts.

In the special series of experiments, ants were presented with the following sequences of turns which are reflected in Table 3. Evidently, most people perceive the sequence of the forks of the 5th and 6th lines of Table 3 as simpler than of the 7th and 8th lines which, in turn, are simpler than the random ones of the same length (lines 13–15). The amount of time for the transmission of information between ants regarding the sequence of the forks appeared increased with the complication of the task (lines 5–8 and 13–15).

This could be proven statistically. We compared the main Hypothesis H_0, the time of the information transmission does not depend on text complexity, with Hypothesis H_1, this time actually depends on it. This experiment consisted of seven series with the sequence of turns of equal length (Table 3: lines 5–8 and 13–15). The total number of the turn sequence orders, according to the duration of the transmission is 7! of which 2! 2! 3! are in line with H_0. The probability of obtaining such an order according to H_0 is very small: 2! 2! 3!/7! = 1/210. Thus, we conclude that Hypothesis H_1 has been realized: the simpler the text the less time for information transmission.

It is interesting that the ants began using regularities to compress only quite large texts: to transmit information of regular sequences of the length "3" of the first and second rows (Table 3) they spent even a little more time than on the

TABLE 3

No	Sequences of the turns	Mean Duration (sec)	SD	Numbers of experiments
1	LL	72	8	18
2	RRR	75	5	15
3	LLLLL	84	6	9
4	RRRRR	78	8	10
5	LLLLLL	90	9	8
6	RRRRRR	88	9	5
7	LRLRLR	130	11	4
8	RLRLRL	135	9	8
9	LLR	69	4	12
10	LRLL	100	11	10
11	RLLLR	120	9	6
12	RRLRL	150	16	8
13	RLRRRL	180	22	6
14	RRLRRR	220	15	7
15	LRLLRL	200	18	5

Duration of transmitting information on the way to the trough by F. sanguinea scouts to foragers (no. 1-8 regular turn pattern; no. 9-15 random turn pattern)

"random" sequence of the same length of the 9th row. So the more time ants spend on the information transmission, the more information—according to Kolmogorov—is contained in the report.

ACKNOWLEDGMENTS

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