



Behavioral Experiments to Understand Animals' Autonomy

森山, 徹

(Degree)

博士 (理学)

(Date of Degree)

1999-03-31

(Date of Publication)

2008-05-30

(Resource Type)

doctoral thesis

(Report Number)

甲1923

(JaLCD0I)

<https://doi.org/10.11501/3156324>

(URL)

<https://hdl.handle.net/20.500.14094/D1001923>

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博士論文

Behavioral Experiments to Understand Animals' Autonomy

(動物の自律性を理解するための行動実験)

平成11年 1月

神戸大学自然科学研究科

森山 徹

DOCTORAL DISSERTATION

Behavioral Experiments to Understand Animals' Autonomy

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January, 1999

ABSTRACT

The concept of autonomy has paradoxical aspect. On the one hand, it is the property of animal itself and seems apart from experimenters, on the other hand, one cannot but find out some significance in it. In order to illustrate such aspect and understand it as essential property of autonomy, I conducted two behavioral experiments.

(Experiment 1; Animals' Own Estimation of Environment; Demonstrated by Turn Alternation in Pill Bugs (*Armadillidium vulgare*))

Fifteen pill bugs (*Armadillidium vulgare*, Isopoda, Crustacean) were examined in 200 successive T-mazes. Though half of them kept turn alternation stable (1), the other half tried to decrease it after learning to keep it (2). In such too much successive T-mazes, keeping turn alternation will accelerate desiccation in their bodies. However, they have tendency to increase it with dry stimulation. In this paradoxical situation, they had better stop turn alternation and escape from it. In order to verify that individuals of (2) estimated such problematic situation and tried to explore another path to escape, all animals were subsequently confronted with fifty choice points, and from the fifty-first choice, the end of the chosen alley was shut. Then the individual turned back and was led to the next choice point. The end of the alley was also shut. In this way they were confronted with successive fifty blind alleys. In this situation, while individuals of (1) continued to move in the apparatus, those of (2) climbed the vertical plain wall and escaped from the apparatus after several trials as if they had estimated the situation as 'closed'. In control experiment, naïve individuals did not climb the wall.

(Experiment 2; Animal Autonomous Choice of Behavior Implying Its Own Spatial Cognition: Demonstration by the Behavioral Experiments in Pill Bugs)

Generally, animal spatial ability is destined to be considered as the selection of the adaptive behavior in the test space by the innate evaluation function. In this paper, I propose to illustrate it as their capacity to create novel behavior resulting from animal-originating estimation of the space.

Eighteen pill bugs (*Armadillidium vulgare*, Isopoda, Crustacean) were individually examined on a disk surrounded by moat. They moved along it with repeating touching and leaving from it because of the innate adaptive locomotive mechanism. Time intervals between one water touching and the next one were measured and sorted in descending order. Then Zipf-scaling behavior was observed in seven individuals while stochastic one in the others. This novel Zipf-scaling behavior seems exploration of routes to escape from the experimental space. It can be considered to result from their notification of such a problematic condition where increases possibility to fall into the water and to die. In order to manifest this novel property, these individuals were consecutively examined on a disk surrounded by slippery wall with partial escaping routs. Then the Zipf-scaling individuals climbed the routs and escaped to the outside while the stochastic ones and naïve ones continued to move along the wall.

ACKNOWLEDGEMENTS

I am grateful to Professor K. Ito for extensive support during this research, and thank Dr. Y. P. Gunji for helpful suggestions and advice. I would also like to thank Mr. Sangen for construction of experimental apparatuses. This study has been supported in part by The Institute of Physical and Chemical Research (RIKEN).

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1. INTRODUCTION

1-1. Understanding of Animals Resulting from Absence of Common Basis

In order to understand an animal's behavior, the experimenter tries to find out common basis between them. He proposes a stimulus to it in order to observe its reaction and to find the basis. For example, he proposes a piece of bread as a stimulus to a dog in order to investigate how it reacts to foods. If the dog eats it, he may infer that the dog has the common basis (in this case, 'notion') of food. I represent this relation as

$$(\text{Bread}) \times [\text{Food}] = (\text{Eat}).$$

To confirm this basis, next experiment is set up. The stimulus is inferred from the basis inferred previously, i.e., [food]. In this way, one can get many equations such as

$$(\text{Orange}) \times [\text{Food}] = (\text{Eat})$$

$$(\text{Meat}) \times [\text{Food}] = (\text{Eat}), \text{ and so on.}$$

However, such common basis does not exist *objectively*. Since it can only be inferred from the finite presentation of stimuli, it is always in unstable state. Namely, there is always possibility to have an unknown stimulus proposed. For this sense, bases are regarded as being indefinite. In spite of such indefiniteness, bases are generally considered as confirmed one. In this stance, animals are considered as machines that have confirmed bases as functions. Then if the dog repeats biting and releasing the proposed egg, the experimenter in the mechanistic stance will consider that, for example, the egg smells bad or the dog cannot distinguish between an egg and a stone. In this case the equation can be represented as

$$((\text{Egg}) + (\text{Bad smell})) \times [\text{Food}] = ((\text{Eat}) + (\text{dose not Eat})) \text{ or}$$

$$(\text{Egg}) \times (([\text{Food}] + [\text{Stone}]) = ((\text{Eat}) + (\text{dose not Eat})).$$

In this way, if one considers the basis 'Food' confirmed, then he must add parameters to the input or function whenever he meets such a contradictory reaction. However, if one admits that bases are indefinite, one can positively understand that the dog uses the egg as 'Toy'. In this case, the equation can be represented as

$$(\text{Egg}) \times [\text{Toy}] = ((\text{Eat}) + (\text{dose not Eat})) = (\text{Play}).$$

In case of human being, though we escape higher unstable place or deep place in the sea on the basis of 'Danger', we do climbing and diving on the basis of 'Pleasure'. We never think that climbers and divers are crazy. If one believes that there exists common bases between animals and us, and regards the bases as functions in animals, he is destined to take a stance of *mechanism*. Animals are regarded as machines that put out specific reactions corresponding to specific stimuli, and the unwanted reactions are defined as errors. The cause of the errors is also definitely identified in the stimuli or in the animals. On the contrary, if one admits indefiniteness of bases, he can also admit the fact that bases are decided necessarily, i.e., without any theoretical *bases*. As a result, understanding of animals entails continuous changing of bases. In calling bases as functions, one can consider that animals can behave without *objective* functions to decide reactions. In this stance, one can consider the changing as continuous creation of novel functions. When this change is regarded as the result from animals' own capacity of identifying environment (or input) (Moriyama, 1998a), such capacity is called autonomy. In order to demonstrate the aspect of autonomous behavior, one must constitute an experiment that seems to have the *objective* common basis, i.e., the dogmatic notion of 'to live' and is also transformed to *subjective* their own basis, for example, decision making or concept making. Recently, several behavioral experiments to show autonomy resulting from their incomplete identification of environment have

been done (Gunji & Kusunoki, 1997; Kitabayashi & Gunji, 1997; Migita & Gunji, 1996). The notion of 'to live' as the common basis has been considered as the universal function for animals to behave and extended to the notion of 'to remain genes'. On this basis, the notion of 'fitness' (Maynard Smith, 1992), 'learning by instinct' (Gould & Marler, 1987) appeared. They believe that animal behavior including evolution and learning can be explained by the notion of 'gene and statistical mutation'. In this case all I want to say is that since we cannot identify the gene's state definitely, we observe the mutation inevitably but can regard it as autonomous behavior in the gene.

1-2. Procedure of the Experiment to Demonstrate Animal Autonomy

Behavioral experiment is a good method to demonstrate animals' autonomy. One can see their interesting behaviors in daily life, and can easily set experimental situations in macro level compared to those of molecular level. As I described above, I defined autonomy as animals' capacity of identifying environment by their own. However, the aim of the experiment is not to find it objectively in animals but to observe that experimenter must do logical jump to find out it. It means that experimenter discards the dogmatic basis of 'to live' to understand animal behavior and inevitably adopts 'their own observation (identification)' to understand that though the basis is indefinite, one can understand them. The procedure of the experiment is shown as the following.

1. We have to find out the animal's regulatory behaviors. A regulatory behavior is defined as a reaction corresponding to a specific stimulus. The behaviors are considered to be selected by natural selection.

2. Next, we have to find out variant behaviors. A variant behavior is defined as a reaction that cannot be decided whether it is a regulatory one or statistical erroneous one. The behaviors are regarded as those that are resulted from 'animals' own observation'. In order to extract such behaviors, one must set a situation that constitutes logical trade-

off. For example, in the previous example of a dog which performed

$$(\text{Egg}) \times [\text{Food}] = ((\text{Eat}) + (\text{dose not Eat})) = (\text{Play}),$$

the egg seems to be food and also stone which can be encoded as [not Food]. So if the dog's reaction is (Eat), then it is regulatory behavior, and if it is (dose not Eat), then erroneous one. But since the actual reaction is ((Eat) + (dose not Eat)), i.e., variance, one can transform the basis from [Food] to [Toy] to explain such a contradictory reaction, ((Eat) and (dose not Eat)), and change it to [Play]. In this way, one can consider the new basis as animals' own identification and the animals constitute it as *subjective* notion. I call this kind of transformation, which is performed to avoid contradiction by observer without any basis, 'logical jump'.

In the previous experiment, one can find out logical jump in the observer. However, such aspect seems so epistemological. In the next step, one must prove the constitution of new basis as animals' obtained capacity. In this process, one can also find out logical jump in animals. The experimenter may constitute a problem-solving situation where the animals that showed variant behaviors can solve it by using the capacity. This kind of solution can be regarded as anticipatory behavior because in the problematic situation they must constitute a model of the situation and their behavior in view of computing its present state as a function of the prediction of the model. Namely, they must predict what happens if they are stayed in the situation and must behave for solution. One can also find out that those that could not show variant behaviors cannot solve the problem. Recently it was demonstrated that by enhancing generation of variants that appeared in the process of learning behavior was used for novel solution on the basis of animals' own identification of environment (Moriyama & Gunji, 1997).

2. EXPERIMENT 1

Animals' Own Estimation of Environment; Demonstrated by Turn Alternation in Pill Bugs (*Armadillidium vulgare*)

2-1. Introduction

Generally, the corner stone of ethological theory is the belief that animal behavior comes in modal action patterns (MAP) (Barlow, 1977). Though MAP was introduced precisely to softened the concept of FAP (Thorpe, 1951) and is considered as properly reflecting the variability among individuals when performing a particular action sequence, one inevitably encounters erroneous behavior in the time sequential series of a MAP in an individual. In this paper, I illustrate that generation of erroneous behavior results not from external noise but from animals' own estimation of environment by experiments of turn alternation behavior in *Armadillidium vulgare*.

Being set in an open field, *A. vulgare* move straight (Iwata & Watanabe, 1957a). It is said that in natural settings, a linear path of movement is the most efficient adaptive strategy to adopt without precise information about environmental resources or hazards (Jander, 1975). When obstacles are encountered, a number of invertebrate species alternate turns, i.e. turn in the opposite direction to a previous turn, and correct the deviations from linear movement (Hughes, 1989a). Such behavior has been also investigated in *A. vulgare* (Watanabe & Iwata, 1956; Iwata & Watanabe, 1957a, b; Kupfermann, 1966). During consecutive trials, a rat placed in the start alley of a two-choice T-maze usually on the second trial chooses the arm that was not visited on the first trial. This phenomenon is considered to be exploratory activity since it reflects the animal's tendency to investigate an unknown part of a new environment (Thinus-Blanc, 1996). On the other hand, it is suggested for terrestrial isopods that the mechanism

underlying turn alternation is based mainly on proprioceptive information about previous turn which arises from bilaterally asymmetrical leg movements (BALM) on the two sides of the body experienced while turning (Hughes, 1985, 1987, 1989b). As the result, turn alternation can approximately be defined as their MAP in an open field with obstacles. In this case, the stereotyped pattern is each 'alternate turn', i.e. one turn and the consecutive turn in the opposite direction, and the variant patterns are the others such as 'turn in the same direction', 'backtracking', and so on. Then, once a MAP is defined, the action sequences that have excessive variant patterns and cause abrupt decrease of its stereotypy are regarded as 'erroneous behaviors'. They are considered as arising from external noise on BALM or inaccuracy of it. The 'inaccuracy' implies some physical problems, for example, weakness of asymmetry, instability of leg movement, and so on. Though in this way, turn alternation can be considered as a stable pattern, it is increased by the temporal effect of desiccation or contact with predator (a spider) (Hughes, 1967; Carbines, et al., 1992). Actually, land isopods are weak against desiccation because of poor waterproofing mechanism (Edney, 1968) and have only such passive defensive ability against spiders as secretion from tegumental glands triggered by their bite (Gorvett, 1956). The adaptive function of their turn alternation has been also concluded as ensuring efficient, direct movement away from biologically unfavorable conditions. These facts imply that their temporal estimation of environment effects on the proprioceptive mechanism of BALM. The objectivism ethologist may consider such effect as resulting from the upper system to control BALM.

On the contrary, in order to manifest that the estimation is the process of temporary identification of unknown environment by referring the previous interaction between themselves and environment in view of determining the temporary action, I constituted especial experiment.

In the past experiments, individuals were examined only three or four successive T-mazes (e.g., Watanabe & Iwata, 1956, Hughes, 1967, Carbins et al., 1992). In such short-path situation, turn alternation may work efficiently. However, in my experiment, each individuals was examined 200 successive T-mazes. In such long-path situation, keeping turn alternation will cause water deficit in their body. However, they have tendency to increase turn alternation with dry stimulation (Hughes, 1967). In this

paradoxical situation, they should notice that turn alternation no longer results in any solution to survive. They had better stop it and escape from the situation. Then they should change their behavior from automatic escaping resulted from BALM or upper control system to autonomous exploring so as to find another path to escape from 'the closed experimental equipment itself' resulted from their own estimation of environment. In order to survive in such environment, they had better have capacity to make temporary models of themselves and environment and change it than have stable mechanism or system to regulate their behavior. This change will be observed as spontaneous increasing of such excessive variant patterns as 'turn in the same direction' or 'backtracking' after keeping long-term turn alternation, i.e. MAP. Such excessive variant patterns are considered as 'erroneous behavior'. Recently such erroneous behaviors resulting in transformation of MAP were investigated in some animals and considered as behavioral plasticity (Gunji, 1996, Migita & Gunji, 1996). In the experiment of route formation in ants, excess generation of pheromone-independent behavior triggered transformation of the route and was regarded as decision making of ant itself (Kitabayashi & Gunji, 1997). In order to verify such excessive generation of variant patterns in *A. vulgare* as resulting from their own capacity of estimating environment, I set another problem-solving experiment which can be solved only by using it.

2-2. Materials & Methods

Subjects

One hundred and fifty individuals of *Armadillidium vulgare* in a bunch were caught on a woodland path in the south foot of Mt. Rokko, Kobe, Japan (34° 43' N, 135° 14' E, 400 ft in altitude) in July for main stock and were kept in a plastic container (20 cm in diameter, with soil to a depth of 2 cm and an opaque thick paper lid) in the laboratory. They were fed on slices of carrot (Heeley 1941). A moist atmosphere was maintained by wetting the soil every day. The lid was kept putting on

and illumination was kept off except for feeding and wetting. The temperature of the laboratory was kept 23-25°C, the humidity was 30-40 %.

In the experimental phase, some individuals, each of which was 8-9 mm in the length and 4-5 mm in the width, were selected among the main stock and were placed into petri dishes (8 cm in diameter, with thin layer of soil) respectively. They were also certified to move actively on the horizontal floor and vertical wood wall. Each individual was left alone and fed on a small piece of sliced carrot for 2 days. A moist atmosphere was maintained by wetting the soil each day. Illumination was kept off except for feeding and wetting.

General Methods

On the third day, they were examined in each experiment. At first each individual was placed into another petri dish without lid and soil, and under light for ten minutes. This sudden bright and dry condition causes their motivation to move. For the light source, a 15-watt fluorescent light that had an intensity of 200 Lx at a distance of 100 cm from the floor of the dish was used. Since white paper was adhered on the floor of the dishes, the soils on their legs were removed while they were moving freely. Then each individual was introduced into the experimental apparatus under the same brightness. One experiment lasted for not more than 30 minutes so that dehydration should not alter their behavior (Warburg, 1964). It was terminated in case that the individual stayed put for more than 2 minutes or escaped by getting over the wall of the apparatus. After the experiment, individuals were returned to each petri dish with lid and soil. All behaviors were recorded by CCD camera connected to an 8-mm video recorder.

2-3. Experiment 1

Methods

In order to constitute long successive T-mazes, I devised an apparatus as shown in Fig.1. The apparatus has two turntables and each of them mounts a T-maze. By turning them, one can constitute any size of successive T-mazes. Two types of mazes were prepared. One has wood walls as shown in Fig.1, and the other has Teflon walls and wood ones as shown in Fig.2. White paper was adhered on the runways to make them move fast (Hughes, 1992). Twenty individuals were selected and each individual was gently lowered into the start alley of one T-maze. As soon as they turned the first T-junction, the turntable was turned to lead them to another T-maze through the connection path. In this way, they were forced to repeat to move from one junction to another. In this apparatus, we can expect to observe their successive alternate turns as shown in Fig.3. Locomotion from one junction to another was defined as one trial, and each individual was examined for 100 trials in wood wall maze (Fig.1) at the first day (experiment 1-1). The same individuals were also examined in Teflon wall maze (Fig.2) for 100 trials on the next day (experiment 1-2) in order to investigate the effect of the texture of the wall on their locomotive activities.

Results

At first, I defined sequential action pattern of '2-3-4' in Fig.3 as 'L-1', and also '4-5-6' as 'R-1'. The complete repetition of these patterns based on BALM was expected in each individual. However, the other patterns (6 patterns, R-2~R-4 and L-2~L-4) illustrated in Fig.4 were also observed. There was no especial difference in between their activities in experiment 1-1 and those in 1-2.

The total number of each sequential action pattern in each individual was counted and shown in Table 1. Individual of No.3 climbed the wood wall and escaped after three trials in both experiment 1-1 and 1-2. Those of No.8 and 10 stayed put for more than 2 minutes from the beginning in both experiments. Individuals of No.9 and 15 moved but in the middle of the trials (No.9, 10th trial in experiment 1-1, 23rd trial in 1-2; No.15, 48th trial in 1-1, 15th trial in 1-2) they stayed put for more than two minutes. Since the amount of each data was so small, they were discarded. According to No.6, No.14 and No.16, though they stayed put in the middle of experiment 1-1 (No.6,

35th trial; No.14, 21st trial; No.16, 8th trial) and the data were discarded, they moved for complete 100 trials in experiment 1-2 and their data were shown in the table. As a result, I investigated the data of fifteen individuals. In the data of total amount of all individuals (the right end of the columns), since the amounts of R-1 and L-1 are obviously greater than the chance level, turn alternation can be approximately considered as the MAP in an open field with obstacles. In this paper, I call L-1 and R-1 'stereotyped patterns', and R-2, 3, 4 and L-2, 3, 4 'variant patterns'. In individual data, since the amounts of each stereotyped pattern are larger than the chance level in the seven individuals of No.4, 6, 7, 13, 17, 18, and 19, turn alternation can be also considered as the MAP in them. I call them 'stereotype group'. On the other hand, in the other eight individuals, L-1 is not significantly larger than the chance level in No.2, 11, and 12, and R-1 is not larger in No.1, 5, 14, 16 and 20. I call them 'variation group'.

Next, I investigated sequential time series of frequency of each stereotyped pattern in each individual to see time sequential stability of them. A set of ten sequential action patterns was picked out in time order, and that is called a 'session'. Frequency of L-1 in a session was calculated as

$$(\text{Number of L-1}) / (\text{Number of L-1} + \text{L-2} + \text{L-3} + \text{L-4})$$

and that of R-1 as

$$(\text{Number of R-1}) / (\text{Number of R-1} + \text{R-2} + \text{R-3} + \text{R-4}).$$

For example, if one observed sequential time series in a session as

$$\rightarrow(\text{R-1})\rightarrow(\text{L-1})\rightarrow(\text{R-1})\rightarrow(\text{L-1})\rightarrow(\text{R-2})\rightarrow(\text{R-1})\rightarrow(\text{L-1})\rightarrow(\text{R-3})\rightarrow(\text{R-1})\rightarrow(\text{L-2})\rightarrow$$

then, frequency of L-1 = $3/4 = 0.75$;

$$\text{frequency of R-1} = 4/6 = 0.67.$$

Then the data of stereotype group were plotted in Fig.5 and those of variation group in Fig.6. The values of SD in R-1 of No.1, 5, 14, 16, 20, and in L-1 of No.2, 11, 12 in variation group are larger than those in the others (Mann-Whitney U-test; $U=46$, $N_1=22$, $N_2=8$, $p<0.05$). This result involves that those eight patterns have big range change in their time sequential series. Such instability of MAP is generally considered as resulting from stochastic external noise or innate inaccuracy of BALM. However, time series of frequencies of R-1 in No.1, 5, 16 and those of L-1 in No.2, 11, and 12 show significant increase from the first session to the first value of '1' (Fig.6). In this way I found out

learning of turn alternation in these six individuals. However, right after the completion of the learning, the value of each learned stereotyped pattern abruptly decreases again, i.e. variant patterns increase, and reach the value below 0.5 except for No.16. I define such action sequences whose values of frequency are below 0.5 as 'erroneous behaviors'. Though the value of R-1 in No.16 did not reach the level of erroneous behavior in these experiments, it did in the next experiment as shown in Fig.6. I call these six individuals 'variation generation group' and two individuals (No.14 and 20) 'error group'. The same tendency, i.e. variant patterns increase right after the completion of learning, was also found in the maze learning without punishment in octopuses (Moriyama & Gunji, 1997). In the other nine individuals of stereotype group and error group, such learning cannot be found out. In order to manifest that variation generation group could notice that keeping turn alternation does not always result in efficiency, and then started to explore another escaping route to get out from the apparatus itself, which resulted in abrupt decrease of stereotyped patterns, I constituted another experiment.

2-4. Experiment 2

Methods

In the next day of experiment 1-2, the same fifteen individuals were examined in the Teflon maze again. In this time, after their turning of the fifty-first T-junction, they were invited to the blind alley situated at the end of the selected arm (Fig.2). Since Teflon sheets are adhered on the walls of the blind alleys, too, they cannot climb them. Then they are expected to backtrack and move to the next T-maze on the other turntable. After turning the next junction, they were invited to the blind alley again. In this way, they were led into blind alleys successively for fifty trials (experiment 2-1).

I also selected another twenty naïve individuals from the main stock and examined in the same apparatus for control experiment. These individuals were introduced to the blind alley from the first trial and were confronted the blind alleys for fifty trials

(experiment 2-2). In addition, the other twenty naïve individuals were examined in the wood maze in which the walls of the blind alleys were also made of wood (Fig.1). They were led to the blind alley from the first trial, too (experiment 2-3).

Results

In the experiment 2-1, all individuals of variation generation group noticed the wood wall of the connection part, climbed it, and escaped from the apparatus in the middle of the experiment (No.1, at 5th trial; No.2, 14th trial; No.5, 11th trial; No.11, 13th trial; No.12, 6th trial; No.16, 18th trial). The other eight individuals except for No.7 of stereotype and error group did not escape and kept moving around in the apparatus for fifty trials. No.7 escaped at 7th trial. As shown in the first and second row of Table.2, number of escaping individuals in variation generation group is significantly larger than that in stereotype & error group. Moreover, in experiment 2-2, sixteen kept moving around, and only two climbed the connection wall and escaped as shown in the third row of the Table. Two stayed put for two minutes from the beginning. The number of escaping individuals is significantly smaller than that of wandering ones (Binomial test: $p=0.0105<0.05$), and equal to that in stereotype & error group (Table 2). These results show that individuals of variation generation group were actually enhanced the capacity of estimating environment in the previous excessive long successive T-mazes (experiment 1) and used it in this 'closed situation' of experiment 2-1. We can conceive emergence of the notion of 'being closed' from the result of the aspect of 'escaping' in these six individuals.

In experiment 2-3, eighteen individuals climbed the corner walls of the blind alleys within two trials and escaped, and two stayed put in the apparatus. The results of experiment 2-2 and 2-3 show that this species climb the wall only as the result of excess struggle of keeping forward going tendency like centipede (Shafer, 1976) at corner-like parts and do not spontaneously climb the vertical walls beside them during moving. It was also reported that woodlice climb vertical wall for transpiration in case of saturated air condition because of the lower humidity of the upper place than lower one (Den Boer, 1961). However, since my experimental condition was dry, they need not have

climbed the wall for transpiration.

2-5. Discussion

In my experiments, I found out learning process of turn alternation and subsequent generation process of erroneous behavior in individuals of variant generation group (Fig.6). The hidden upper system to sense the temporal desiccation and control the lower system of BALM can be inferred to explain this learning in such context of general ethological theory as neo-Darwinism (e.g., Maynard Smith, 1982). In such a stance, learning is regarded as an instinctive behavior (e.g., Gould & Marler, 1987). In this idea, it is expected that once the value of frequency of L-1 or R-1 keeps 1 stable, the appearance of erroneous behaviors is considered as resulting from the effect of external noise on or inaccuracy of the inferred upper system. Otherwise, another system must be inferred for the explanation of transition from the learning process to the generation process of erroneous behavior. However, such inference is contradictory because turn alternation is guaranteed as the efficient action for escaping as described in the extant results. As the result, the appearance of erroneous behavior is exactly considered as resulting from the stochastic external noise or internal inaccuracy. On the contrary, in view of theory of learning machines, the process which repeats learning and generation of error is considered as typical learning way of Boltzmann Machine (Ackley, et al., 1985). In such a machine, the objective of learning is merely decreasing the energy of the system and the error is statistically given to it as heat for increasing the energy again in order to search much lower energetic state. Anyway, in both notions, learning and error are arisen from different mechanisms, and the learning is completed automatically by the interaction between the mechanism and environment. Moreover, the most important and essential premise to realize these kinds of learning is that once the learning individual receives the surrounding environment (in another word, input, or a stimulus) as X at time t (represented as $X(t)$), it can identify the other X in the past (represented as $X(t-n)$) with the $X(t)$. Otherwise, any learning based essentially on reinforcement can not be realized. It involves that animals can identify X at any time

and take no time for identification. However, this complete identification of environment results in discrimination between learning and error, and makes the idea that animals are complex machines that have multiple hierarchy of different systems controlling with each other. On the contrary, since $X(t)$ is regarded different from $X(t-n)$ in the actual animals because of absence of any objective basis to guarantee their equivalence, they take real time to identify them. In this case, the identification is considered as a process with actual time span. However, by accepting such process, one must admit the fact that animals cannot finish the identification in finite time. For example, when they try to identify $X(t)$ with $X(t-1)$, at first they have to recall the information of $X(t-1)$ from their memory. However, while recalling it, since time goes by and $X(t)$ changes into $X(t+1)$, they must identify $X(t+1)$ with $X(t)$. However, while recalling $X(t)$, since $X(t+1)$ changes into $X(t+2)$, then Though, in this way, identification with time span results in infinite regression of environment as input, animals behave against $X(t)$ in the same manner with high probability as against $X(t-1)$. In this process, one cannot but admit the idea that animals identify $X(t)$ with $X(t-1)$ not by an objective basis but by their own temporary one. It means that they treat them as same things without any objective basis while knowing them different. Though such arbitrary identification is theoretically incomplete because the process never finishes, one can admit the notion of animals' own identification. Such local process of identification can be found out in any interaction between animals and environment. I call such incomplete identification 'animals' own estimation'. The estimation can be observed as the process of temporary identification of unknown environment ($X(t)$) by referring the previous interaction between themselves and environment ($X(t-1)$) in view of determining the temporary action pattern. Such estimation was clearly appeared as the transition from the learning process to variation generation process in the individuals of variation generation group.

It has already suggested that turn alternation results from proprioceptive mechanism of BALM (Hughes, 1985, 1987, 1989b). For example, if they turn left at previous junction ('2' in Fig.3), the movement of the legs on the left side of the body (i.e. legs on the in-corner) becomes slower than that on the right side (out-corner). However, after turning, the speed is exchanged, i.e. the left side becomes fast and the

right side slow in the runway, because of their tendency of asymmetry. As a result, at the next junction they turn to right ('4' in Fig.3). It has been reported that the present turn angle increases with greater preceding ones, and tend to become smaller than the preceding ones (Kupfermann, 1966; Hughes, 1985). From these results, one can conclude that the magnitude of the asymmetry is directly dependent on the preceding turn and gradually decreases in the successive T-mazes. However, there is a way to enhance it and keep turn alternation. That is to increase the same direction turns. It has also been reported that present turn angle increase with the number of preceding forced same direction turns (Watanabe & Iwata, 1956; Hughes, 1985). It means that when an individual approaches a T choice point requiring two preceding right (or left) turns (two-turn maze), the tendency of its turning in opposite direction is further enhanced in comparison with the situation of only one preceding right (or left) turn (one-turn maze). From these past results, it is expected that the tendency of turn alternation is automatically compensated, and we can see the aspect in the results of seven individuals in Fig.5 (No.4, 6, 7, 13, 17, 18, and 19). In the graphs, the values of frequency randomly move up and down but around high mean value. However, in the individuals of variation generation group, the values gradually increase for very long period, i.e. show the aspect of learning. In this case, we cannot but infer that they spontaneously made the magnitude of asymmetry larger than the preceding ones, i.e. the decision of the magnitude is not directly dependent on the preceding turn angle but depend on their own estimation after turning. I suggested that the estimation is the process of temporary identification of unknown environment by referring the previous interaction between themselves and environment in view of determining the temporary action. In my experiments, the environment is each T-maze. Since they cannot know whether the end of the selected alley is connected to another T-maze or not, e.g. closed, extended further, and so on at the moment of confronting with the choice point, the present environment is considered as unknown one. They can only determine the magnitude of asymmetry by chance. As the result, in Fig.6, the initial values of frequency of stereotyped patterns which show learning tendency are very low (mean=0.376, n=6) and near chance level (0.25) while the other values except for those of R-1 in No.14 and 20 are very high (mean=0.742, n=22). However, they increase the values by estimating such unknown

environment by referring the previous interaction. For example, in Fig.3, the individual at '5' predicts the existence of runway extended to opposite direction of the previous turn and increases the speed of legs that were once the in-corner legs at '4' by referring the pervious result of '3'. Namely, turning to right at '4' was resulted from increasing the speed of left legs by the prediction of extended right-runway during 3. In the six individuals of variation generation group, while one of the stereotyped patterns in each individual show learning pattern, the other one keeps high value as shown in Fig.6. By referring the high value one, the other one was gradually increased. However, we also find the generation of excessive variant patterns after the completion of the learning (Fig.6). In order to explain such phenomena, one must infer another cause such as external noise or another system to cause such errors as described above if one infer the machinery learning system. On the contrary, if one admits the capacity of animals' own estimation of environment, such generation of erroneous behavior necessarily appears without adding the other systems. In this notion, the completion of learning involves the completion of identification of environment. Namely, in the graphs of the six pill bugs in variation generation group, both values of R-1 and L-1 reach 1 (except for No.12) at the point of completion of learning. At this point, they completely adjusted the magnitude of asymmetry of leg movement in the runway by predicting the following runway extended to the opposite direction of the preceding turn. For these animals, the environment (each T-maze) is no longer unknown but already known because they completely predict the forthcoming situation and probably construct the image of 'subsequent infinite zigzag runway'. However, such individuals inevitably find out or constitute another unknown environment because they are always in ongoing process of estimating unknown environment by referring the previous result, i.e. already known environment. In my experiment, once they constitute the image of infinite zigzag runway, they immediately realize the unknown environment, i.e. the environment that contains the whole runway. As a result, they try to go to the outside world of the zigzag runway in order to identify it, and explore the way. As the result, they have to cease repetition of alternate turns. Their graphs show immediate decrease of the frequency of the learned stereotyped patterns. In this way, we can explain the learning and generation of variant actions in terms of animals' own estimation of environment. In this stance,

one do not have to add another system or cause to explain the generation of variant patterns. They inevitably appear as the result from natural expansion of the process of their own estimation of unknown environment. Unfortunately, I could not find out such clear aspects in the other nine individuals. I think the difference is depending on the extent of the capacity of their estimation.

By the way, even though I suggest the idea of animals' own estimation of environment, one cannot easily adopt the idea because he can also explain the previous results by the notion of learning machine or additional program to occur noise statistically. In order to show that they exactly tried to move to the outside of the infinite zigzag runway, I set experiment 2-1. In experiment 1, by taking variant patterns, they could virtually get out of the zigzag way. However, in experiment 2-1, their strategy was thoroughly denied by the blind alleys. If they were learning machines, all they can do would be to keep moving in the apparatus. However, because of their enhanced or expanded capacity of estimating environment and obvious presentation of boundary condition by blind alleys, it is expected that they identify that this environment is closed situation and notice the surrounding environment more easily than do in experiment 1. As the result, they certainly escaped from it by climbing the plain wood wall. On the other hand, in the other nine individuals, only one individual climbed. That population is significantly lower than that in variation generation group (Table.2). Such climbing behavior is quite novel because few naïve individuals which did not experience such a long successive T-mazes climb plain walls as investigated in experiment 2-2 (Table.2).

In this way, there is strong significant correlation between enhancement of capacity of estimating environment and the emergence of novel behavior. The novel behavior is strictly the outside entity against such instinctive one as MAP, learning by instinct, and learning machines. Such outside entities are generally considered as errors or results from the other mechanism. Of course it is appropriate method to try to describe animal behaviors by definite mechanism if one try to consider them as machines. However, even in such a stance, one will distinguish between animals and machines. On the other hand, if one tries to understand animal's intangibility as autonomy, he must feature the negative erroneous behavior and illustrate it as positive efficient behavior. For the experimenters, such paradoxical behavior can be recognized as novel behavior. In my

experiments, variant patterns generated after learning in the experiment 1 can be considered as novel behavior, however, we can see them only as erroneous behaviors and cannot see them as efficient ones. Then, in order to manifest that they were necessarily resulted from the animals' own estimation of environment and not from stochastic external noise, I set experiment 2-1. In the experiment, they were given obvious boundary condition by means of encountering blind alleys and could use climbing behavior as efficient escaping behavior. Recently, in the learning experiment of maze solution by octopus, we also found out learning process and variation generation process in the first experimental phase. Then we observed novel solution of maze in the second phase that enhanced generation of erroneous behaviors but could be solved by their capacity of estimation of environment (Moriyama & Gunji, 1997). In this sense, erroneous behaviors can be considered as leftover resulted from the process of their own estimation of environment. Moreover, the computer models based upon the notion of animals' estimation, which is the process of temporary identification of unknown environment by referring the previous interaction between themselves and environment in view of computing the temporary action, were reported. They illustrate autonomous transition between schooling and disperse in fishes (Gunji & Kusunoki, 1998) and that between homing and exploring in other fish (Migita & Ueda, 1998). Behavioral experiments based upon the same idea were also reported and show emergence of novel behavior as the usage of 'tool' in food-retrieving behavior in ants (Kitabayashi et. al, 1999) and as also climbing behavior by pill bugs in the other situation (Moriyama, 1998).

If one considers that animals' estimation of environment 'X' can be performed by the existence of complete image of 'X' in them, he has to infer the machinery mechanism or mysterious consciousness which constitutes it. On the contrary, I admit incompleteness of such image as 'X' because it takes infinite time to get theoretically complete image of it. Such aspect was experimentally constituted as the infinite successive T-mazes in experiment 1. Even though the zigzag runway extended infinitely, the individuals autonomously set boundary and tried to move to the outside of the autonomously constituted environment. In this way, animals' estimation of environment always entails such movement to the outside and it can be considered as their own

capacity. I could illustrate that the capacity entails the emergence of novelty, which is the outside of experimenter's logic. Such capacity is considered as autonomy and positively found out by understanding impossibility of dividing the observer's viewpoint from the animal's one.

2-6. Figures and Tables

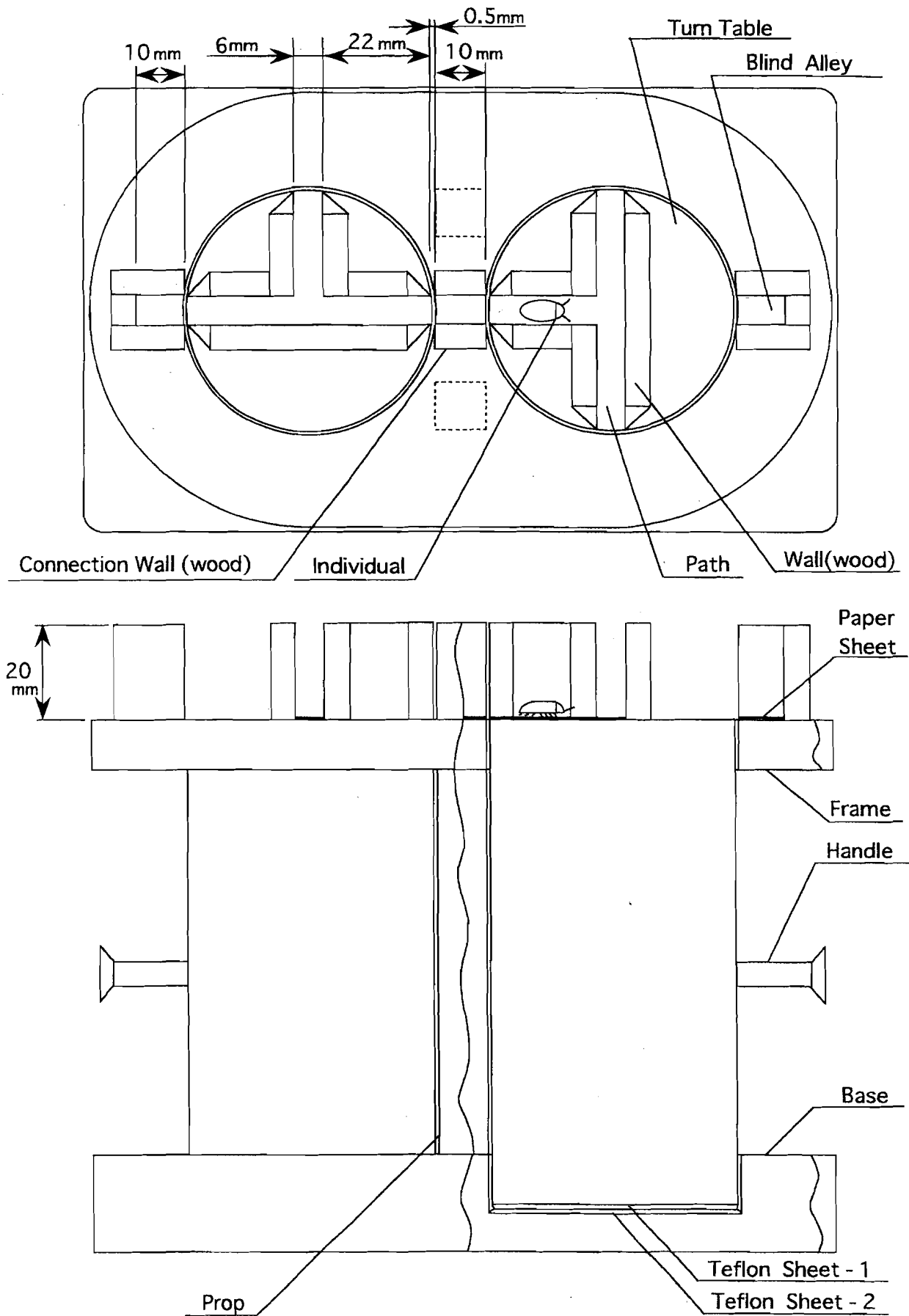


Fig. 1

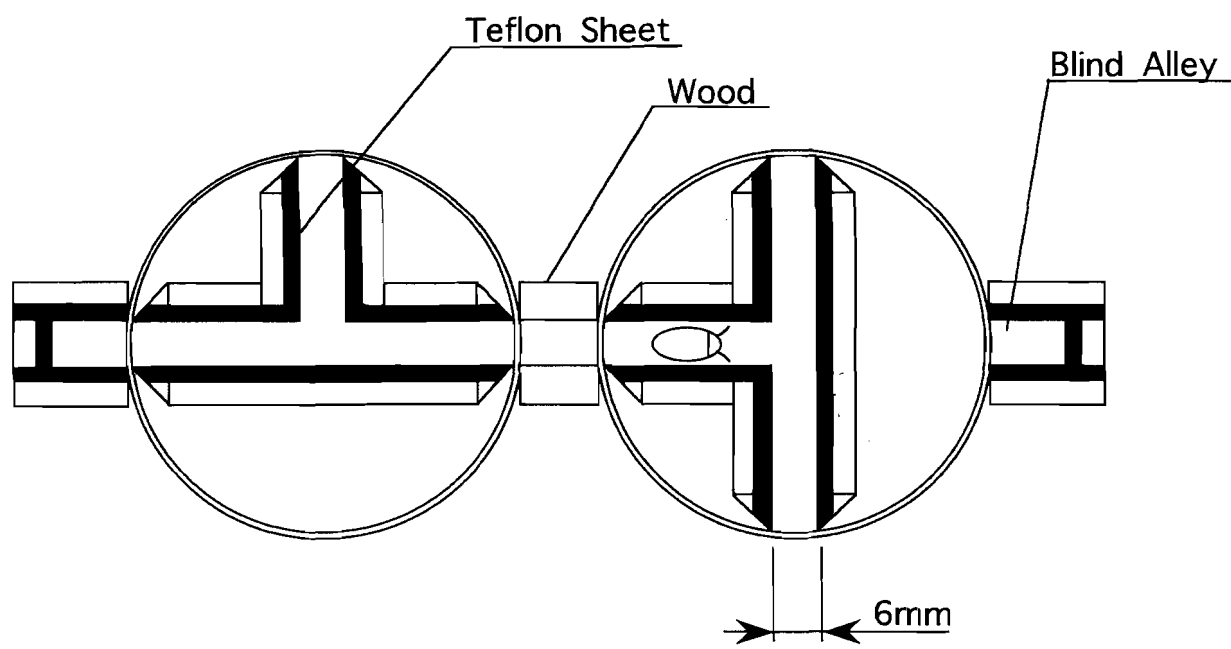


Fig. 2

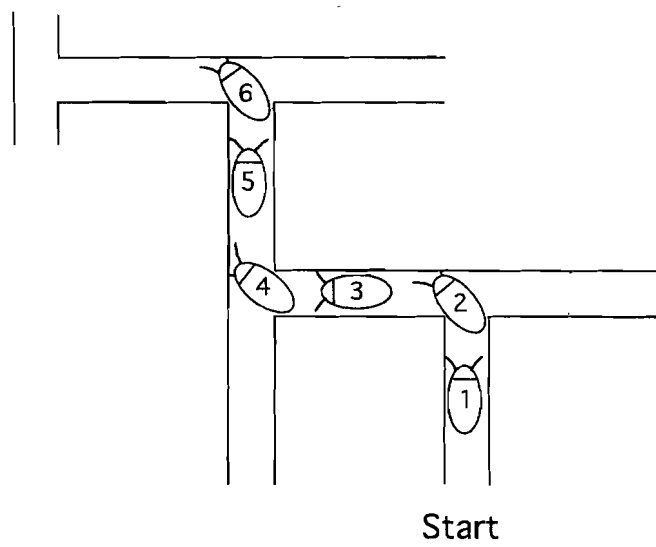


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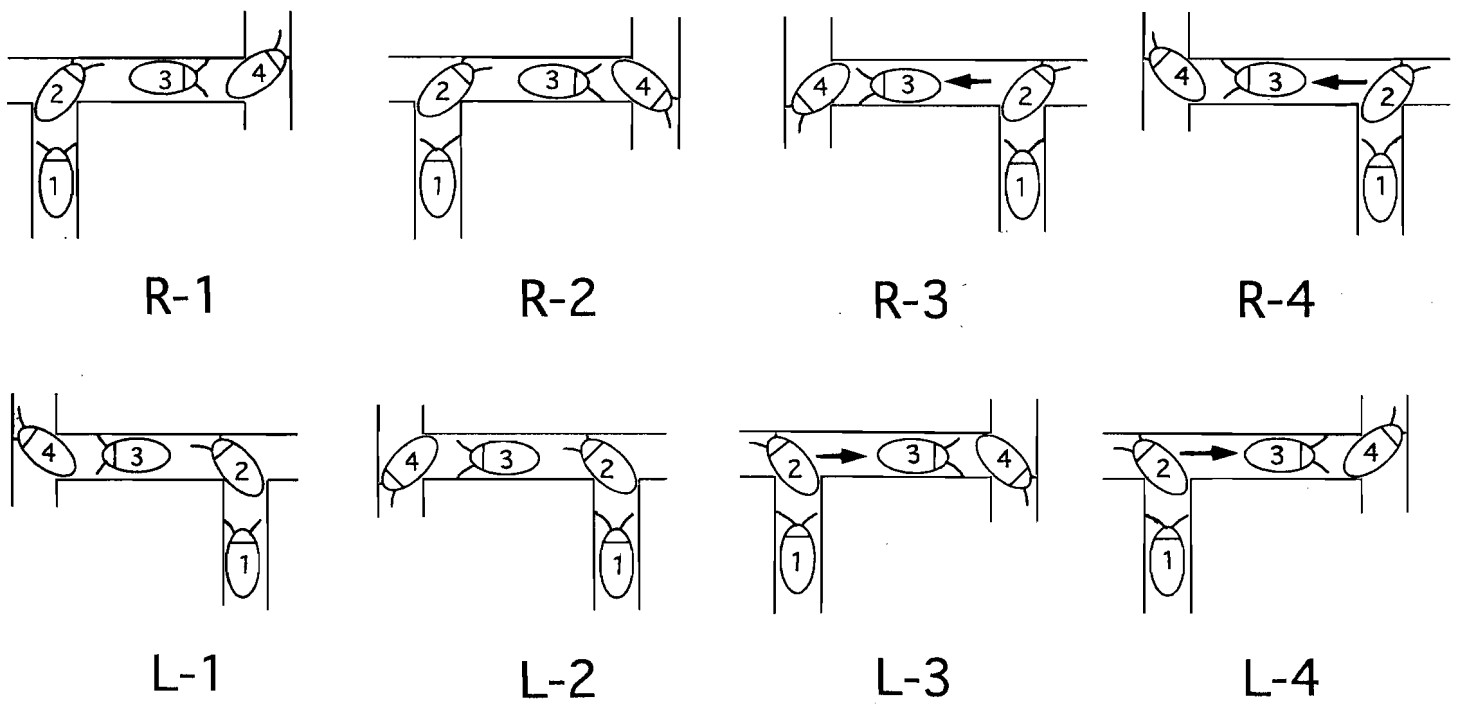
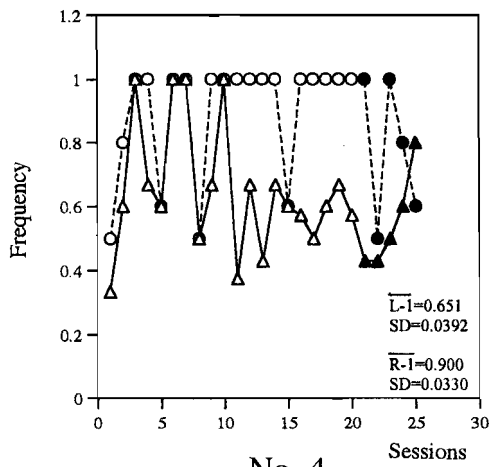
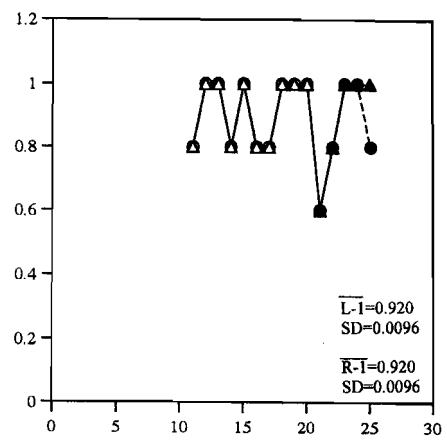


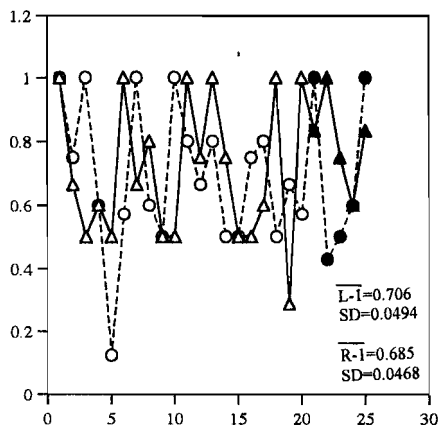
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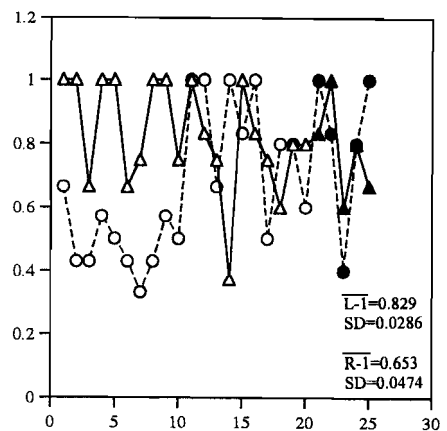
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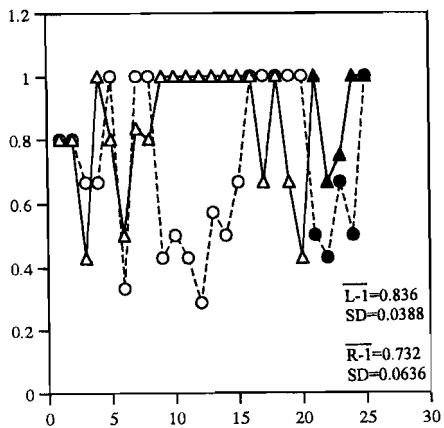
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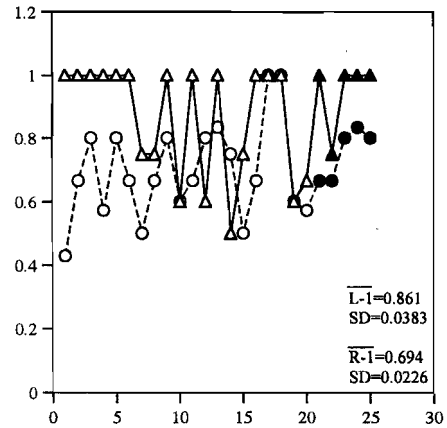
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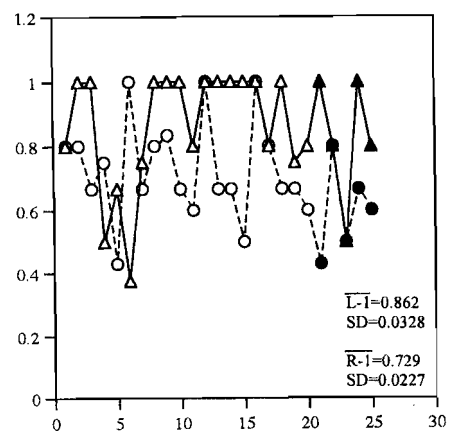
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Fig.5

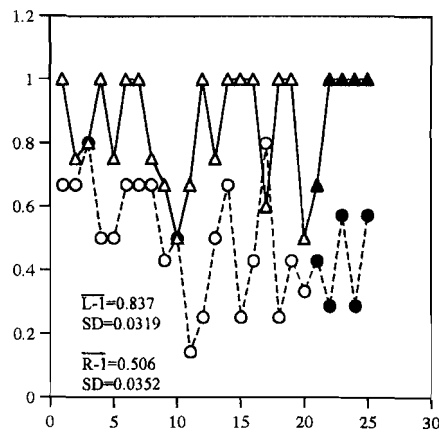
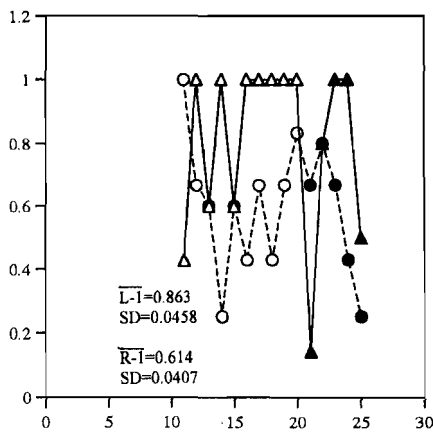
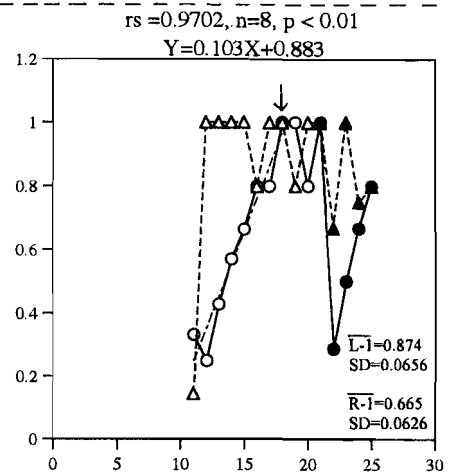
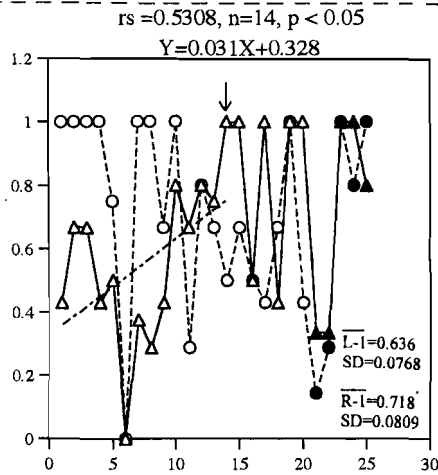
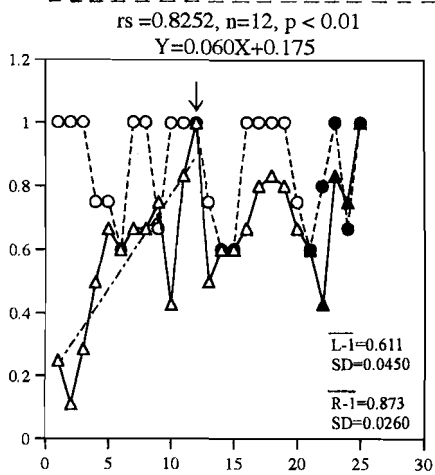
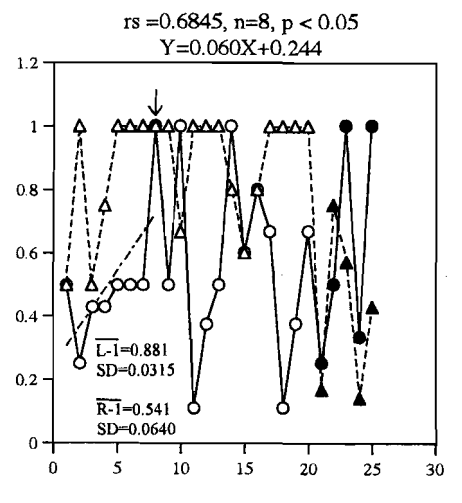
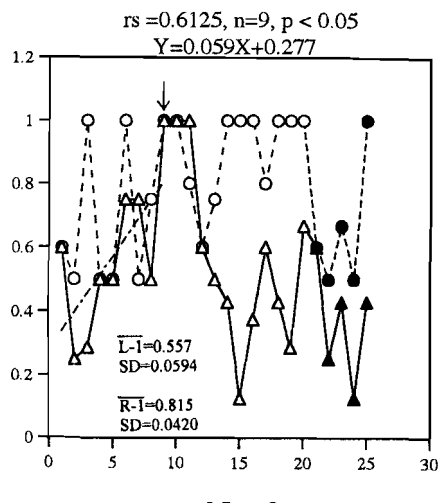
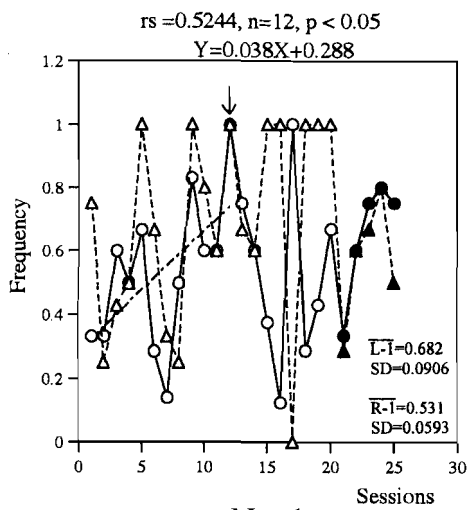


Fig.6

Table 1 Number of sequential patterns

	No.1	No.2	No.4	No.5	No.6	No.7	No.11	No.12	No.13	No.14	No.16	No.17	No.18	No.19	No.20	Total
L-1	59	65	73	62	46	67	68	63	68	33	36	75	75	78	59	927
L-2	17	29	42	8	4	25	41	28	13	4	4	18	7	11	9	260
L-3	1	2	1	3	0	2	3	3	1	1	1	0	3	0	3	24
L-4	6	25	3	0	0	4	7	15	3	3	3	1	3	3	1	77
Total	83	121	119	73	50	98	119	109	85	41	44	94	88	92	72	1288
χ^2	14.75	ns	6.13	35.63	35.28	13.22	ns	ns	30.60	15.24	17.82	33.36	43.68	44.52	29.39	248.51
R-1	52	64	72	63	46	66	70	64	70	34	34	74	77	77	62	925
R-2	46	12	5	53	4	27	8	22	34	21	17	30	34	27	60	400
R-3	5	3	2	1	0	1	1	1	0	0	2	1	0	1	0	18
R-4	14	0	2	10	0	8	2	4	11	4	3	1	1	3	6	69
Total	117	79	81	127	50	102	81	91	115	59	56	106	112	108	128	1412
χ^2	ns	30.39	49.00	ns	35.28	8.17	42.98	15.04	5.43	ns	ns	16.64	15.75	19.59	ns	135.87

Table 2 Number of escaping individuals

	Escaping	Wandering	
Variation generation group	6	0	p=0.0014<0.01
Stereotype & error group	1	8	
Naive individuals	2	16	p=0.4708>0.05

Figure Legends

Fig.1; The apparatus to construct infinite successive T- mazes with wood wall. Each turntable mounts a T-maze, and has a handle to be turned manually. Teflon sheets adhered to both turntables' bottom and receptacle parts of the base decrease friction between them to have turntables operated smoothly. One can have each individual experienced T-maze successively by turning the turntables. As a result, each alley of T- mazes becomes 54 mm. The slight vacancy (0.5 mm) between connection wall and the T-maze can be disappeared by means of slightly pushing the turn table to the connection wall. One can also introduce the individuals into the blind alleys. They are not used in experiment 1, but used in experiment 2-3.

Fig.2; The apparatus to construct infinite successive T-mazes with Teflon wall. All the wall except for connection wall are covered with Teflon sheet. It also has blind alleys with Teflon wall. They were used in experiment 2-1. The other structure is same as that of experiment 1 (Fig.1).

Fig.3; The illustration of turn alternation. The Arabic numbers show the time sequential locomotion of the individual. The individual is turning in the opposite direction to the preceding turn. The sequential action pattern '2→3→4' is defined as 'L-1'. That of '4→5→6' as 'R-1'. They are called 'stereotyped patterns' in this paper.

Fig.4; Variation of variant patterns (L-2, 3, 4, and R-2, 3, 4), and stereotyped patterns (L-1 and R-1) . The Arabic numbers show the time sequential locomotion of each individual. In L-3 (R-3) and L-4 (R-4), the individuals are trying to turn to the left (right) at the choice point, however, change the direction before reaching the next point.

Fig.5; Time series of frequency of L-1 (triangles) and R-1 (circles) in stereotype group. Open symbols are the data from experiment 1-1 and 1-2 (from session 1 to 20). Closed ones from experiment 2-1 (from session 21 to 25). Mean (L-1, R-1) and standard deviation (SD) in the first 20 sessions (i.e. experiment 1-1 and 1-2) of each pattern are shown in each graph. Individual number is shown below each graph.

Fig.6; Time series of frequency of L-1 (triangles) and R-1 (circles) in variation group. In the graphs which show learning pattern, value of Spearman rank correlation coefficient (r_s), the sample size (n), significant level (p), and the function of the regression line that is represented by long-and-short-dashed line are shown above each graph. The sample for r_s is the points from the first session to the session where the value of frequency becomes 1 at first. Namely, this span involves learning process. Vertical arrow indicates the completion point of learning.

3. EXPERIMENT 2

Animal Autonomous Choice of Behavior Implying Its Own Spatial Cognition: Demonstration by the Behavioral Experiments in Pill Bugs

3-1. Introduction

The survival of many species is considered to depend on their ability to use spatial knowledge (e.g., Thinus-Blanc, 1996). This spatial ability is estimated in such spatial tests as radial arm maze (Olton & Samuelson, 1976), water maze (Morris, 1981), and so on. In every test, the solution is given by the experimenters in advance, which is the most effective behavior for survival. Then the individuals that learn to take such a behavior are considered to have spatial abilities. In this way, once the solution is given in advance, the spatial ability is regarded as that to select the most effective behavior among the selection domain consisting of the variety of behaviors inferred in the test space. This ability seems to be the same as that of robots which have the evaluation function and the encoding system of the spatial information, e.g., places in the environment, the angular and distance relationships between those places, to constitute the selection domain. In case of animals, the brain, especially hippocampus and parietal cortex (e.g., McNaughton et al., 1989) in it, is considered as such an encoding system. However, the criterion of the selection, i.e., the evaluation function, is still originated in experimenters' concept. It implies that one can not find out animal-originating spatial ability, which involves the choice of behavior based upon animal's own evaluation of the test space, as far as they consider that the solution is the most effective behavior for survival. Generally, animal spatial cognition involves their construction of spatial representation, i.e., such spatial information as in robots. However, in this paper, I propose to consider animal's own evaluation of the space as spatial cognition and

especially call it 'spatial estimation'. I also call the choice of the solution behavior resulting from this spatial estimation 'autonomous choice'. Then, because the behavior resulting from the animal-originating spatial ability, i.e., their autonomous choice of behavior, does not seem effective behavior for survival, it will be found out in case that although animals perform ineffectively against survival, the experimenters inevitably regard the behavior as the solution. Since the extant behaviors are considered to remain because of its effectiveness, experimenters have to constitute especial test space to make them inevitably perform ineffectively, where the more animals try to take effective behavior, the more they increase ineffectiveness against survival. This condition makes the evaluation function no longer work appropriately, in another word makes animals not to select the behavior for survival among the extant selection domain consisting of the predictable behaviors in the space. For experimenters, their description of animal behaviors becomes unstable. If they were robots, they would encounter danger of death in such a condition. However, if they notice the condition, i.e., estimate it, they will create the novel behavior for survival even though it will seem ineffective because of such a paradoxical condition. So, this novel behavior will be observed as the unpredictable outside entity of the selection domain. This choice of the outside entity implies the autonomous choice and the notification of invalidity of evaluation function does spatial estimation. In this way, since instability of observers' description of animal behaviors gives animal's own spatial estimation, one can find out it even in those without highly organized central nervous system like brain. Once one finds out an effective spatial behavior for survival and tries to explain the realization of the effectiveness only by the interaction between animals and the space, he inevitably gets into machinery thinking and introduces the concept of evaluation function. However, he can contradictorily use machinery thinking to escape from itself and can constitute special experiments as the models to understand animal autonomous choice and spatial estimation.

Detour behaviors are usually taken as proving spatial representations and its abilities have been demonstrated in several species of mammals and birds (e.g., Chapuis, 1987, Krushinskii, 1970). Even in some invertebrate species, they do turn alternation, i.e., turn in the opposite direction to a previous turn when obstacles are encountered and

show detouring. The function of the behavior is considered as the automatic correction of the deviations from linear movement (Hughes, 1989a). It is said that in natural settings a linear path of movement is the most efficient adaptive strategy to adopt without precise information about environmental resources or hazards (Jander, 1975). In pill bugs, *Armadillidium vulgare*, straight movement (Iwata & Watanabe, 1957a) and turn alternation (Watanabe & Iwata, 1956; Iwata & Watanabe, 1957a, b; Kupfermann, 1966) have been also investigated. It is suggested for terrestrial isopods that the mechanism underlying turn alternation is based mainly on proprioceptive information about previous turn which arises from bilaterally asymmetrical leg movements (BALM) on the two sides of the body experienced while turning (Hughes, 1985, 1987, 1989b). In this way, this species can constitute efficient direct escaping behavior away from biologically unfavorable conditions by BALM. When they encounter obstacles, they can turn, move along it and turn in the opposite direction to the previous turn at the edge of it. However, in my experiment, they were surrounded by moat filled with water. This species cannot survive in water. In this case, though it is assumed that they move along it by the effect of BALM and inhibitory reaction against water, such behavior will increase possibility to fall into it. It means that BALM defined as the effective mechanism for survival results in death in that especial condition. This paradoxical experimental condition indicates the limitation of machinery explanation of animal behaviors, i.e., instability of observers' description of animal behavior, and becomes a model to understand their autonomous choice of behavior and their own spatial estimation. In order to find emergence of the novel behavior resulting from autonomous choice and also to quantitatively show it, Zipf analysis (Zipf, 1949) was applied because Zipf's law is emergent in the sense that is not obvious consequence of the underlying dynamical rules (Bak, 1996).

3-2. Materials & Methods

Subjects

Two hundred individuals of *Armadillidium vulgare* (Fig.1) were caught in the garden of our university situated on the south foot of Mt. Rokko, Kobe, Japan (34° 43' N, 135° 14' E, 400 ft in altitude) for main stock. They were kept in a plastic container (20 cm in diameter, with soil to a depth of 2 cm and an opaque thick paper lid) in the laboratory. They were fed on slices of a carrot (Heeley 1941). A moist atmosphere was maintained by wetting the soil every day. The lid was kept putting on and illumination was turned off except for feeding and wetting. The temperature of the laboratory was kept 23-25°C, the humidity was 30-40 %.

General Methods

For the experiments, some individuals, which were 8-9 mm in the length, 4-5 mm in the width and not in molding, were selected among the main stock and placed into petri dishes (8 cm in diameter, with thin layer of soil) respectively. They were also certified to move actively on the horizontal floor and vertical wood wall. Each individual was left alone and fed on a small piece of a sliced carrot for 2 days. A moist atmosphere was maintained by wetting the soil each day. Illumination was turned off except for feeding and wetting. On the third day, they were examined in each experiment. At first each individual was placed into another petri dish without lid and soil, and under light for ten minutes. This sudden bright and dry condition causes their motivation to move. For the light source, a 15-watt fluorescent light that had an intensity of 200 Lx at a distance of 100 cm from the bottom of the petri dish was used. Since white paper was adhered on the floor of the dishes, the soils on their legs were removed while they were moving freely. Then each individual was introduced into the experimental apparatus under the same brightness. One experiment lasted for not more than 30 minutes so that dehydration should not alter their behavior (Warburg, 1964). It was terminated in case that individual stayed put for more than 2 minutes or escaped from the apparatus by climbing its wall. After the experiment, individuals were returned to each petri dish with lid and soil. All behaviors were recorded by the CCD camera connected to an 8-mm video recorder.

3-3. Preliminary experiments

Experiment 1

In order to investigate their linear movement resulting in escaping from the bright, dry condition, twenty individuals were selected and examined whether they could move 100 mm within plus or minus 10 mm on the plain white linoleumed floor (Fig.2). It has been reported that white floor makes isopods move fast (Hughes, 1992). Each individual was examined only once.

Results

75%, i.e., 15 individuals in 20, cleared the criterion ($\chi^2 = 5.00$, $p < 0.05$) and were certified to take linear movement when they were exposed in the bright, dry condition.

Experiment 2

In order to investigate that they correct the deviations from the initial linear movement when they encounter obstacles by means of turn alternation based on BALM, the other twenty individuals were selected and examined whether they can turn in the opposite direction to the preceding turn at the obstacle (Fig.3). Each individual was put on each side of the board alternately and examined for twenty trials with 30 seconds intervals in each side.

Results

When they had turned to right in encountering the board (1 in Fig. 3), they turned to left at the edge of it in the probability of 72 %, i.e., 144 trials in 200 ($\chi^2 = 38.72$, $p < 0.001$). When they had turned to left in encountering the board (1' in Fig. 3), they

turned to right at the edge of it in the probability of 85 %, i.e., 170 trials in 200 ($\chi^2 = 98.00$, $p < 0.001$). In this way, it was certified that turn alternation works to correct the deviations from the initial linear movement when they encounter obstacles.

Experiment 3

In order to investigate that they cannot escape from the closed enclosure which implies the obstacle with infinite width because their escaping strategy is considered to consist of the linear movement and the turn alternation, the other ten individuals were selected and put in the cylinder (Fig. 4 (a), (b)). Each individual was left in it for 15 minutes (900 seconds) and examined only once.

Results

Six action patterns were observed as shown in Fig. 4 (a) and (b). The time spent for each action pattern was measured (minimum unit = 1 second) in each individual. Only one individual climbed the wall (action pattern C) and escaped from the cylinder although all of them have ability to climb on such a rough texture wall. In the cylinder, they moved forward along the wall (action pattern F) for 86.7 % (mean, $N=10$) in the experimental period, i.e., 780.3 seconds in 900 (mean). This strong tendency to move along the wall can be considered as the result of the turn alternation. In this experiment, they show linear movement after being put on the center point of the floor and encounter the wall. Then for example, they turn to left. In turning at the wall, the proprioceptive mechanism of BALM works and the legs on the left side of their body try to move faster than those on the right side do. As a result, their locomotive vector toward the wall and they move along the wall with the right side of their body touching to it. Additionally when they returned (action pattern R), they changed the direction of locomotion as shown in Fig.4 (c) by the effect of BALM. In case of the figure, after the individual turned to left (1→2), they are doing an about-face (3→4→5→6→7) because of excessive movement of the legs on the left side of its body. Though they sometimes stood up and leaned on the wall as shown in 5' in their returning, most of them (nine

individuals) did not climb the wall and continued to move from 5' to 6 and 7.

3-4. Main experiments

Experiment 1

The other twenty individuals were selected and each of them was put on the center of the plain disk illustrated in Fig.5 (a). They were left for 15 minutes. The disk was surrounded by moat filled with water. Since the water inhibited their linear movement from the starting point, they were expected to move along the water as same as they did in the cylinder (preliminary experiment 3). However, in this condition, moving along the water will increase possibility to fall into it. Since they cannot live in water, they had better stop moving. However, once they are put on the disk, it is considered that their instinctive linear movement is stimulated and they inevitably encounter the water. Then another instinctive BALM also works and they are expected to walk along the water which must be inhibited. This paradoxical experimental condition indicates the limitation of complete machinery explanation of animal behaviors and becomes a model to understand their autonomous choice of behavior implying their own spatial estimation. If they were robots, they would only encounter danger of death. However, if they notice the condition, i.e., estimate it, they will create the novel behavior for survival even though it will seem ineffective because of such a condition. So, this novel behavior will be observed as the unpredictable outside entity of the selection domain by means of special analysis. In this experiment, I applied Zipf analysis (Zipf, 1949).

Results

Expectedly, they mainly took forward locomotion (F in Fig. 4) along the water with the other four action patterns defined in preliminary experiment 3 except for climbing action. Two individuals unfortunately fell into the water (Of course they were saved as soon as they fell). In the forward locomotion, they sometimes touched the

water by their both antennae, another time by only one antenna, and the other time they moved without touching the water as shown in Fig.6. In these three kinds of the antenna-reactions, the two-antennae reaction can be considered to be the most dangerous one because their body were leaned forward to the water. However, this behavior inevitably occurs as the result of turn alternation based on BALM (see caption in Fig. 6). In view of machinery thinking, such a contradictory behavior can be considered to occur by chance. On the contrary, in view of considering animal-originating spatial ability, there is possibility to find out effectiveness in such a contradictory behavior. In order to quantitatively investigate whether the two-antennae reaction occurs only by chance or not, I applied Zipf analysis. The statistical study of language demonstrates that the word frequency distribution follows a hyperbolic law (Zipf, 1949). In the Zipf analysis, a histogram that gives the total number of occurrences of each word in the text is elaborated. Then one can draw a curve showing how many words appear with more than a given frequency. It equivalently shows the relative ranking of words versus their frequency. Such a curve is found to be linear on double logarithmic paper. In the same way, the curve showing the number of cities in which the population exceeds a given size (or equivalently, the relative ranking of cities versus their population) also follows the Zipf's law (ibid.). In this way, Zipf's law can be found in a lot of natural phenomenon and considered to be emergent in the sense that is not obvious consequence of the underlying dynamical rules (e.g., Bak, 1996). Recently, it was found out in immune system (Burgos, 1996). In my experiment, I measured every time interval between two-antennae reactions as shown in Fig.6. Each reaction is distinguished with each other in view of how long it takes to be occurred after the preceding one. Then the curve showing the number of two-antennae reactions of which the potential time from the preceding reaction exceeds a given time was made in each individual and represented in the form of double logarithmic graph of the relative ranking of reactions versus their potential time. The typical examples are shown in Fig.7 (a) and Fig.7 (b). Similarly in Fig.7 (a), every curve in eight individuals (No.1, 2, 3, 4, 6, 15, 16, and 18) showed approximately straight line with slope near unity (Table 1). It involves that their intervals distribute not stochastically but have some correlation with each other. From this result, one can consider the sequence of two-antennae reactions

showing Zipf-scaling behavior not as insignificant repetition of water touching. On the other hand, similarly in Fig.7 (b), every curve in seven individuals (No.7, 8, 9, 10, 11, 13, and 19) showed approximately arc line which implies exponential function (Table.1). It implies that the intervals distribute stochastically. Individuals of No.5, 14, 17 and 20 stayed put for more than 120 seconds in the middle of the experiments and their experiments were terminate, and then I could not get enough amounts of plots (less than ten plots) for the analysis. Individuals of No.6 and 12 fell into the water. In order to manifest that the eight individuals that showed Zipf's law were enhanced the capacity to estimate the environment, i.e., they noticed the closed situation, and created a novel behavior, which implies their exploration of water boundary, I set another experiment.

Experiment 2

The other twenty individuals were selected. Each of them was put on the center of the plain disk illustrate in Fig.5 (a) and was left for 15 minutes in the same way as experiment 1. Then consecutively, an acrylic cylinder without top and bottom with partial paper walls was put on the disk (Fig.5 (b)). In this way, the boundary condition of the disk suddenly changed into slippery wall with partial rough walls. Each individual was consecutively left for 15 minutes. It was concluded in preliminary experiment 3 that naïve individuals do not climb vertical wall even though its texture is rough. In this experiment, it is expected that some individuals show Zipf-scaling behavior in the water-surrounding condition. Moreover, they are expected to climb the paper wall and escape from the wall-surrounding condition as the result of application of the exploratory behavior obtained in the water-surrounding condition. Another naïve ten individuals were tested in the apparatus illustrated in Fig.5 (b) as the control. They were given wall-surrounding condition from the beginning.

Results

Since two individuals (No.7 and 18) stayed put for more than two minutes in the water-surrounding condition, eighteen individuals were examined in both conditions.

Eight individuals could climb the paper wall and escaped from the apparatus while only one individual could in the control group. Though the difference between those amounts did not reach statistically significant level enough (Fischer's exact probability test, $p=0.06335>0.05$), number of climbing individuals actually increased by precedent introduction of the water-surrounding condition. I also did Zipf analysis in the eighteen individuals (Table.2). Six individuals in the seven that showed Zipf-scaling behavior had shown climbing behavior, and only two in the eleven that showed stochastic behavior had done so. The difference between those amounts is significantly different (Table.3). In the table, we can also see that the difference between the amount in the exponential (i.e., stochastic behavior) individuals and that in the naïve ones is significantly equal. In this way, there is strong coefficient between appearance of Zipf-scaling behavior and that of unpredictable positive climbing behavior. This result implies novelty of the Zipf-scaling behavior and makes us consider it as exploratory behavior resulting from their spatial estimation, i.e., notification of the closed space.

3-5. Discussion

In my experiment, by introducing the water-surrounding condition which gives unstable description of animal behavior to the observer, number of climbing individuals actually increased (see results of main experiment 2). It was reported that woodlice do not climb vertical walls except for transpiration in case of saturated air condition because of the lower humidity of the upper place than lower one (Den Boer, 1961). Since my experimental condition was dry (humidity, 30~40%), they did not need to climb the wall. Actually, naïve individuals, which did not experience water-surrounding condition, did not (see results of preliminary experiment 3 and Table. 3). In this sense, wall-climbing behavior in my experiment seems ineffective for survival because it does not work for transpiration but merely increases desiccation in them. Desiccation is one of the most serious conditions for them and therefore their habitat is limited to such dark and damp places as under stones, fallen leaves, and so on. However, it is also serious to stay in the apparatuses shown in Fig. 5 for long time. In this case, climbing behavior

contradictorily seems effective because they can have opportunity to find out damp places by getting out from them. In this sense, it can be considered as the novel behavior for escaping. Then the most interesting thing is that the appearance of climbing behavior in the wall-surrounding condition strongly correlates with that of Zipf-scaling behavior in the precedent water-surrounding condition. The Zipf-scaling individuals performed the novel wall-climbing behavior (Main experiment 2, see Table.3). Naïve individuals, which did not experience water-surrounding condition, and non-scaling individuals did not (ibid.). Recently, it was reported that just before appearance of the novel food-retrieving behavior of the ants, in which they carry the food on the other big one by pulling the big one as if they considered it as tool, Zipf-scaling behavior was observed (Kitabayashi, 1999). In the water-surrounding condition, one can only expect the stochastic occurrence of the two-antennae reactions based upon proprioceptive mechanism of BALM and water-inhibitory reaction, which are considered to remain to realize survival in nature. In this way, they are considered to move based on these two machinery mechanisms. However, some individuals showed Zipf-scaling behavior, which indicates that they does not obey any obvious mechanisms, and experimenters cannot but consider it as novel behavior created by the animal itself. On the contrary, one can consider this Zipf-scaling behavior to appear by chance. However, as described above, this behavior exactly contribute to arise the other novel escaping behavior. This result concludes the Zipf-scaling behavior to be novel exploratory behavior to find out escaping route as the result from notification of closed condition surrounded by water. If the Zipf-scaling behavior had appeared by chance, the correlation with the climbing behavior would not have occurred. In this way, the ineffective repetition of two-antennae reactions against survival got to be the effective exploring behavior for survival. This behavior is novel and the outside entity of selection domain, which consists of stochastic repetition of two-antennae reaction, staying put, and falling into the water, in that condition. This autonomous choice is considered to result from their spatial estimation, i.e., the notification of ineffectiveness of selection among the selection domain, in another words, invalidity of evaluation function. This capacity of spatial ability was also observed in the wall-surrounding condition. They also created novel escaping behavior. These autonomous choice and

spatial estimation were found out by conducting paradoxical water-surrounding condition which enhanced instability of observers' description of animal behavior based upon effectiveness for survival. In the maze (with transparent partitions) solution in octopus, by conducting a paradoxical condition where their effort to move fast in the path contradictorily results in decreasing the speed, they decreased the time to detour the partition as if they had looked over the whole maze (Moriyama, 1997). Recently, in the discrimination learning of turtle, it was reported that ill-suited experiment which can be proved neither success nor not by experimenters derive their own learning implying autonomous choice (Nomura & Gunji, 1999). Generally, animal survival is considered to be realized by selecting and combining modal action patterns, MAP (Barlow, 1977), which is regarded as the most elementary behavioral unit. Even in the high level process of spatial cognition, once one considers it as extant ability to realize survival effectively, it is also regarded as evaluation function like robots to select the most effective behavior among the selection domain consisting of the variety of behaviors inferred in the space. Then, in this stance, ineffective behaviors against survival are regarded as errors. In this way, by discriminating effective behaviors and ineffective errors, the description of animal behavior becomes complete and stable. However, by this stable description, one cannot represent animal-originating evaluation of the space because the criterion of effectiveness is given by the experimenters in advance. In case of pill bugs, the main mechanism to cause locomotion along the water or wall is generally considered to result from machinery mechanism of BALM (see Fig. 6). BALM is considered to constitute efficient escaping behavior in the open field with obstacles (Hughes, 1967, 1985, 1987, 1989b, Carbins et al., 1992). When they encounter the desiccate condition or predators, linear movement will help them to leave far from such undesired conditions most promptly. So they move straight in being put in such a condition (preliminary experiment 1). However, there are many obstacles in natural conditions. If they cannot detour one of them, i.e., stop in front of it or return backward, they will be destined to encounter those conditions again. In actual, by means of turn alternation, they can detour it and move efficiently away from such conditions. This notion of efficiency is based only upon experimenter-originating belief of universality. Namely, although one cannot investigate infinite conditions to determine the efficiency of the behavior, he

believes the possibility of its universal usage from the results of finite experiments. Then, in order to guarantee such universality, the test space to estimate its efficiency is constituted by the observer and he can get to observe the effective behavior for survival in anytime in this selected test space. In this way, the notion of infinitude of environments is converged into a selected test space. Since the effectiveness for survival in animal behavior is defined in such test spaces selected by observers, the description of animal behavior is actually incomplete and unstable. What makes it complete and stable is only experimenter's belief. This notion of instability of observer's description looks pessimistic at a glance. Though as if it denied the description of animal behavior, it does not insist to do so. On the contrary, by taking it into account, one can find out animal-originating spatial ability as the result of animals' own estimation (or evaluation) of environment not as that of machinery evaluation function. In the mechanistic stance, since all behaviors are considered to appear based on innately programmed mechanisms, unexpected behaviors are considered as errors or to be resulting from the other hidden mechanism. In this way, all behaviors become predictable in principle. In this paper, I conducted paradoxical experimental condition to enhance instability of observer's description of animal behavior and illustrate animal-originating spatial ability as autonomous choice of behavior. Then the exploratory behavior was found out as its result, semantically by the correlation with the novel climbing behavior for escaping in the following experiment and quantitatively by the Zipf analysis. While one characteristic of Zipf-scaling behavior, which is emergent in the sense that is not obvious consequence of the underlying dynamical rules, implies its originality in animals, another one dose their intangibility, which also involves their autonomous aspect. As shown in Fig. 7 (a), the relation between time interval t and the rank shows power function, i.e., $t = c \times (\text{rank})^a$. This relation can be changed into $(\text{rank}) = N(t) = c' \times t^{-(1/\alpha)}$. In this equation, $N(t)$ implies the number of time intervals identified in which the time exceeds a given t . When defining $P(t)$ as the existence probability of a time interval whose amount is t , there is a relationship of $P(t) \propto N(t)$. Then one can get a relation $P(t) \propto c' \times t^{-(1/\alpha)}$. As long as this kind of power function, even in $t \rightarrow \lambda t$, the distribution type of time interval never changes (Takayasu, 1986). This unchanged distribution of time interval implies that even when one identifies the state of the animal

as staying put, the repetition of two-antennae reactions is folded in it. Namely, the animal moves at the moment when the observer identifies its state. In this sense, even though one tries to identify their behavior, he cannot do it in finite time. This aspect illustrates animal intangibility implying its autonomy. By considering instability of observer's description, such intangibility in animals appeared, and I could illustrate animal autonomous choice and their own spatial estimation. I demonstrated the methodology to understand animal intangibility as their positive autonomy.

3-6. Figures and Tables

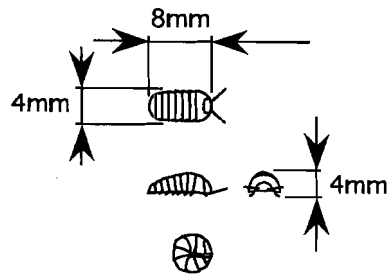


Fig. 1

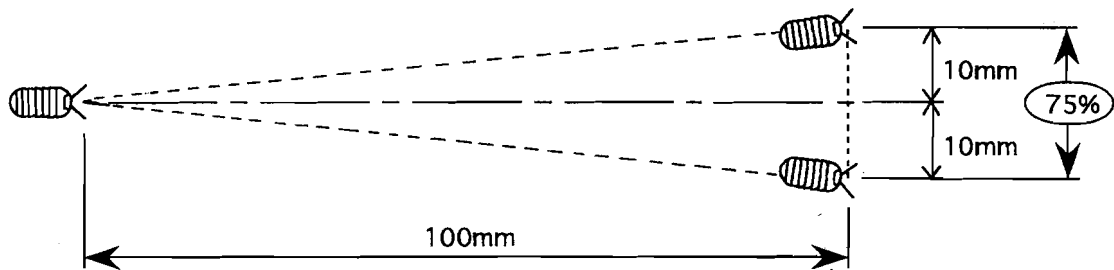


Fig. 2

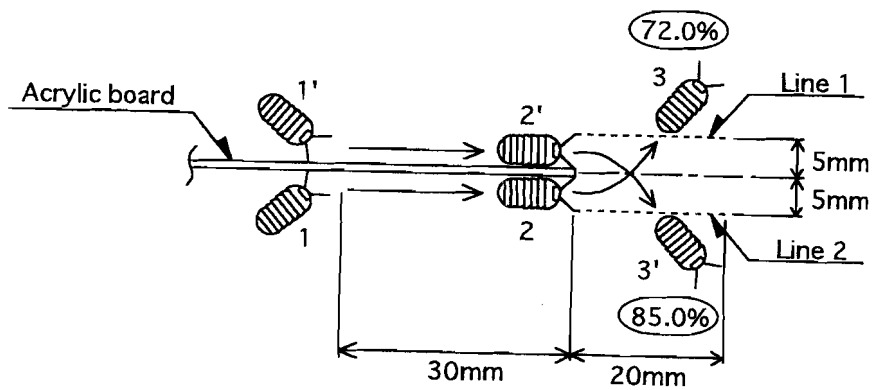


Fig. 3

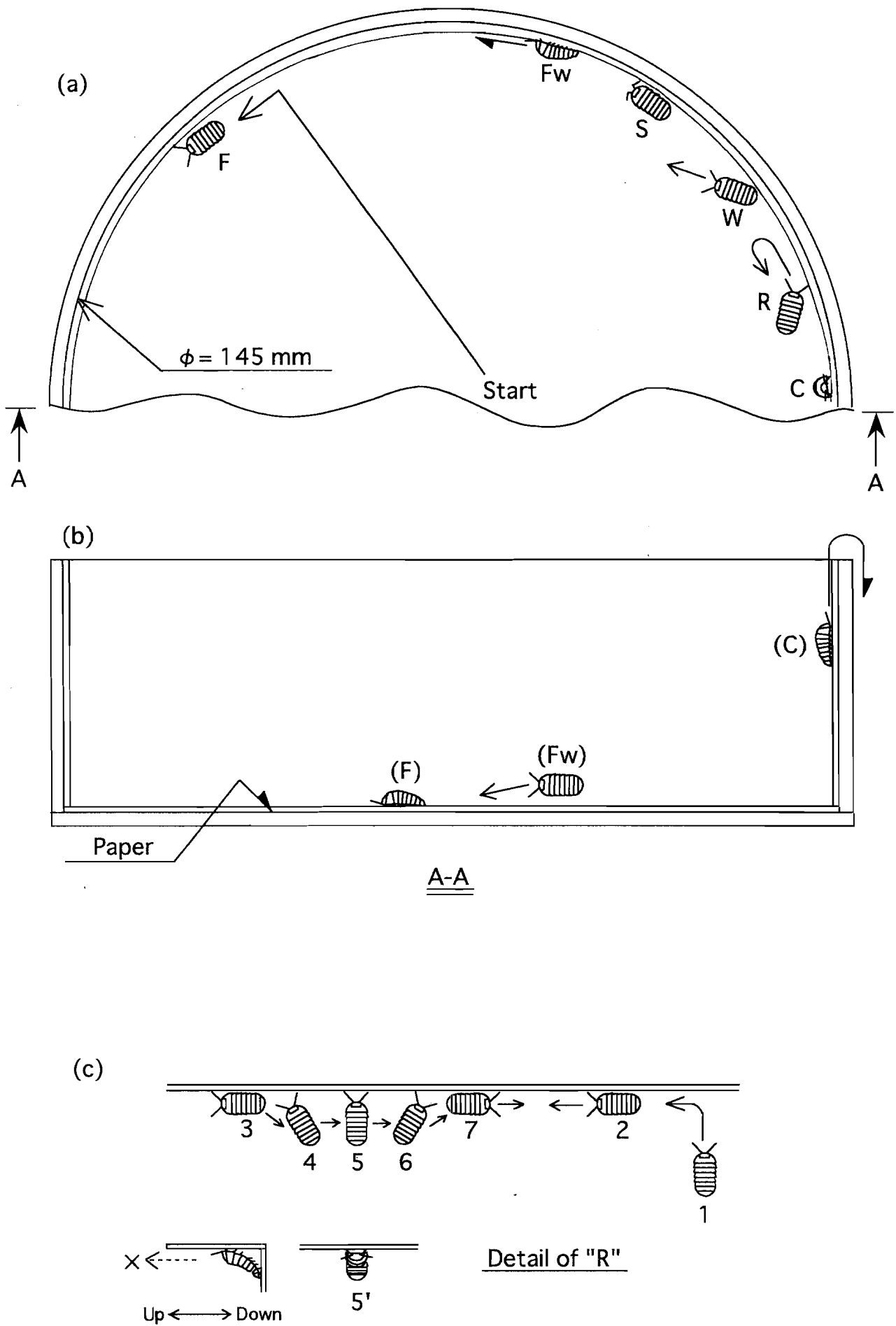


Fig. 4

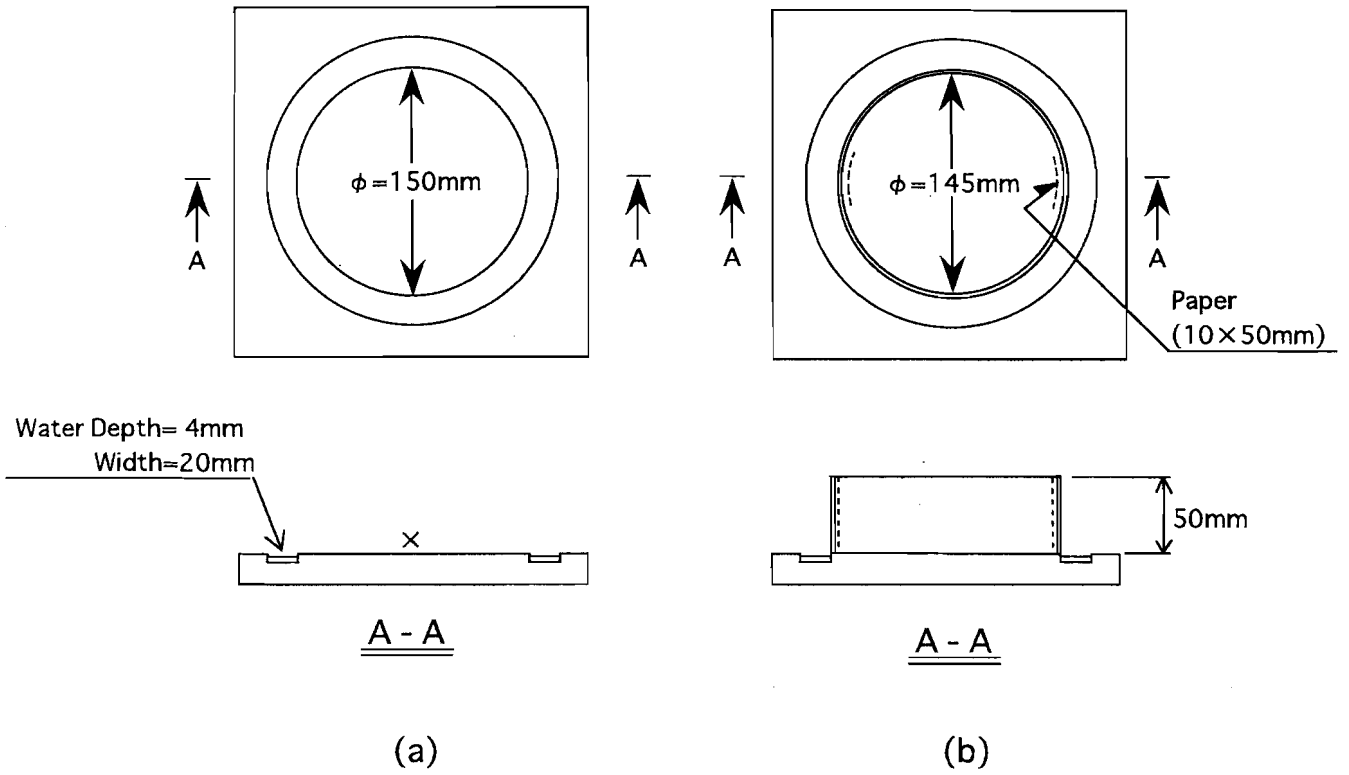


Fig. 5

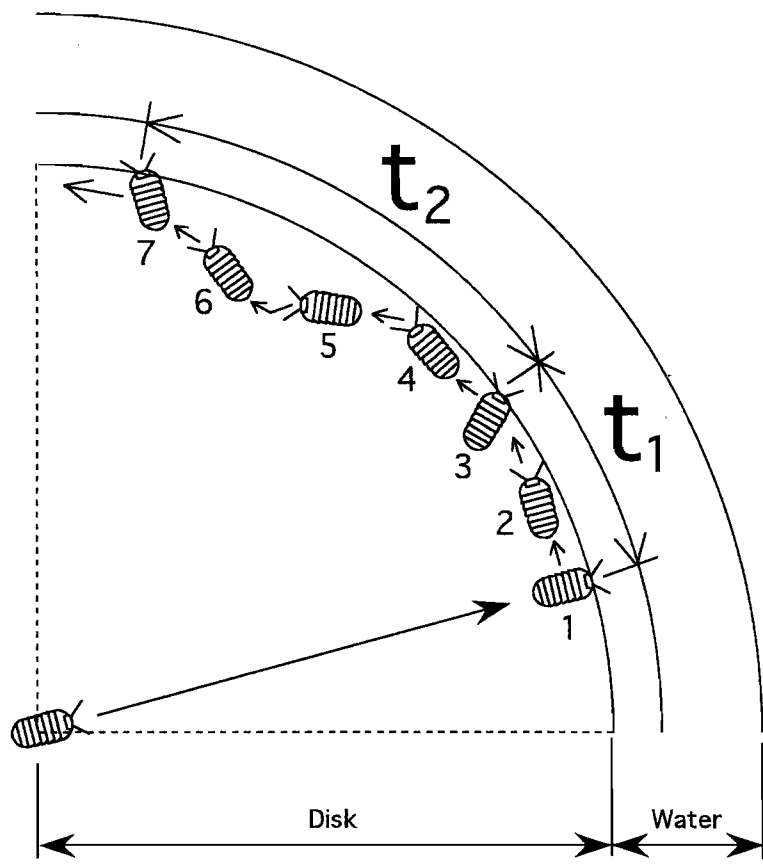


Fig. 6

No. 2

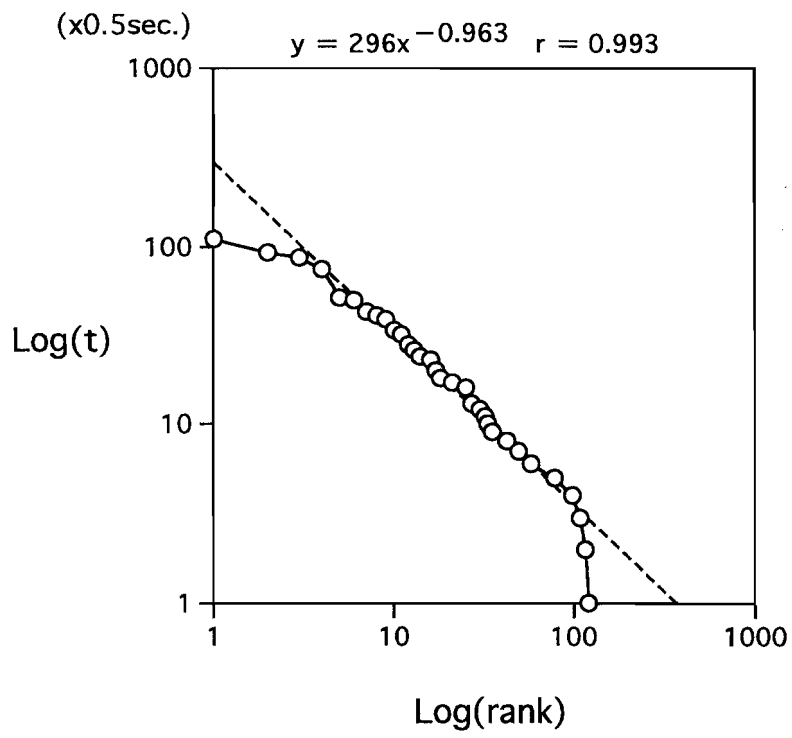


Fig.7 (a)

No. 9

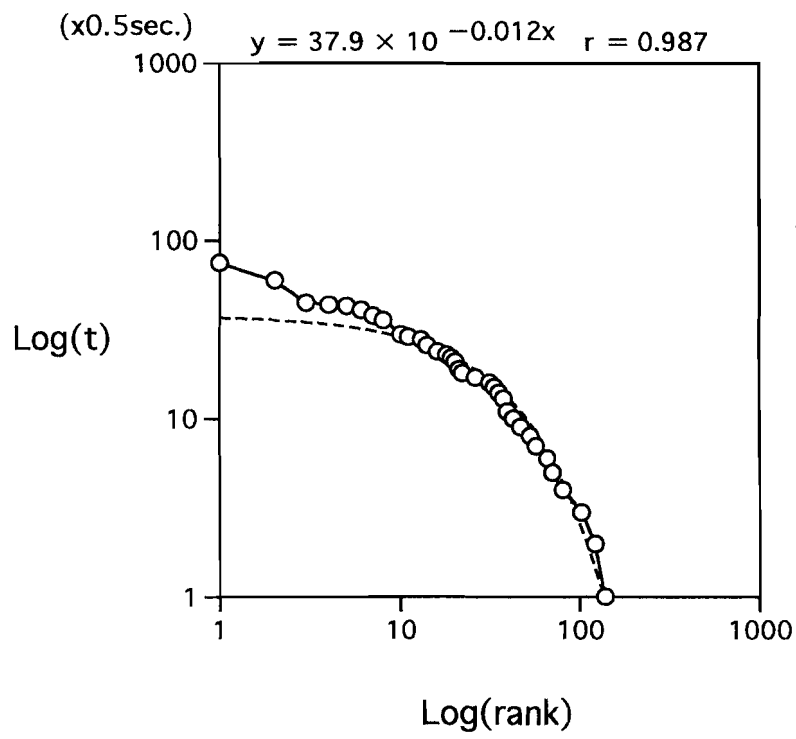


Fig. 7(b)

Table. 2 Regression lines of Zipf's law and exponential function in main Exp. 2

	Zipf				Exponential				Escape
	-a	r	n	N	-b	r	n	N	
No. 1					0.01	0.97	29	32	
No. 2					0.01	0.97	23	25	
No. 3					0.02	0.98	33	36	
No. 4					0.01	0.97	27	30	
No. 5					0.02	0.99	31	34	O
No. 6					0.01	0.99	27	30	
No. 7	-	-	-	-	-	-	-	-	
No. 8	0.76	0.96	26	28					O
No. 9	0.78	1	21	23					O
No.10					0.01	0.97	27	30	
No.11	1.04	0.98	31	34					O
No.12	0.92	0.99	28	31					O
No.13	0.94	0.98	32	35					
No.14	0.87	0.97	27	29					O
No.15					0.01	0.97	29	32	
No.16					0.02	0.99	33	36	
No.17	1.06	0.99	21	23					O
No.18	-	-	-	-	-	-	-	-	
No.19					0.02	0.99	30	33	
No.20					0.04	0.98	28	31	O

Table. 3 Number of escaping individuals

	Escape	Wander
Zipf-scaling	6	1
Exponential	2	9
Naïve	1	9

*p = 0.0088 < 0.01

*p = 0.4135 > 0.05

*Fischer's exact probability test

Figure legends

Fig.1; Size of the experimental subject, *Armadillidium vulgare*. Their habitat is such damp and dark places as beneath bark, stones, piles of fallen trees because of their weakness against desiccation. They can conglobate their body to protect the attack from predators and desiccation.

Fig.2; Investigation of the linear movement. 75%, i.e., 15 individuals in 20, could move 100 mm within plus or minus 10 mm on the plain white linoleum floor.

Fig.3; Investigation of turn alternation. When having turned to right in encountering the white vertical acrylic board, they turned to left at the edge of it in the probability of 72 % (1→2→3). When having turned to left in encountering the board, they turned to right at the edge of it in the probability of 85 % (1'→2'→3'). Turning to left after leaving the edge was defined when they moved across the Line 1. Turning to right, the Line 2.

Fig.4; (a) Actions in closed enclosure (upper view); (b) Actions in closed enclosure (side view). Paper with rough texture is adhered on the surface of the apparatus. F...Forward movement, Fw...Forward movement on the wall, S...Stay put, W...Wandering apart from the wall, R...Return, C...Climbing; (c) Detail illustration of R (upper view). Sometimes they accidentally lean on the wall in the middle of the process as shown in 5' (upper view). The side view is shown on the left side.

Fig.5; (a) White acrylic disk surrounded by moat filled with water. Individuals were put on the center of it (×) at the beginning of the experiments.; (b) White acrylic disk surrounded by transparent acrylic wall. This apparatus is constructed by putting transparent acrylic tube on the white acrylic disk illustrated in (a). Two rectangle papers (10×50 mm) were adhered on the wall and formed partial rough parts. In both apparatuses, the surface was cleaned by air-brush after each experiment.

Fig.6; Time intervals between two-antennae reactions. 1, 3, and 7 represent two-antennae reactions. t_1 and t_2 are time intervals. Each behavior was identified by pausing the video at intervals of 0.5 second. In this figure, the individual turned to left at the first encountering of the water (1 to 2). Then by the effect of turn alternation based on BALM, it tries to turn to right (3). However, there is moat filled with water, it leaves from it and turns to left (3 to 4). Then in this case, though it gets moving away from the water (4 to 5), turn alternation works again and it turns to right (5 to 6). Then it encounters the water again (7). In this way, the animal moves along the moat.

Fig.7; (a) An example of Zipf-scaling curve (Individual No. 2). The values of time interval (t) were sorted in descending order (rank) on the double logarithmic graph. The unit of the time is 0.5 second because the behavior was identified by pausing the video at intervals of 0.5 second. Individual number, the equation of the regression line and its correlation to the plots (r) are represented above the graph. 90 % of the whole points were selected (see Table. 1) to cut off the ones on both ends, and both hyperbolic equation and exponential one were fitted to the selected part as regression lines. The one which has correlation value (r) with more than 0.95 is decided as the appropriate regression line. The correlation value which exceeds 0.95 means that more than 90 % of the plots are predicted by the equation. The exponent implies the slope of the line.; (b) An example of exponential curve (Individual No. 9). The plots showed approximately arc line which implies exponential function. This kind of curve implies the stochastic repetition of two-antennae reactions. Individual number, the equation of the regression line and the correlation to the plots (r) are also represented above the graph.

Table. 1 and 2;

Zipf's law... $Y=C \cdot X^{-a}$

Exponential function... $Y=C \cdot 10^{-bx}$

r ... Correlation value between regression line and plots

n ... Number of selected points to decide regression line (90 % of N)

N ... Whole number of points

4. CONCLUSION

In the two experiments based upon simple procedures, I could illustrate the aspect of autonomy with duplicated meaning, i.e., on the one hand, it is the property of animal itself and seems apart from experimenters, on the other hand, observers cannot but find out some significance in it. I hope my work will help many fields especially investigating the concept of 'self'.

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