The dynamics of long term exploration in the rat
Part II. An analytical model of the kinematic structure of rat exploratory behavior

Ofer Tchernichovski[1,*], **Yoav Benjamini**[2]

[1] Department of Zoology, George S. Wise Faculty of Life Sciences, Tel-Aviv, Israel
[2] Department of Statistics and Operation Research, The Sackler Faculty of Exact Sciences, Tel-Aviv University, Tel-Aviv, Israel

Abstract. A simple analytical model is proposed here that captures to a large extent the kinematic structure of rat exploratory behavior. Previous studies have shown that such behavior consists of regular excursions into the environment from a preferred place termed a home base. In the first part of this study, we showed that with time and repeated exposure to the same large environment, there is a gradual increase in the length of excursions. Concurrently, the rat's velocity pattern changes in a complex yet structured way, which is correlated with the exposure ($=$familiarity) to places. In this part, we show that the complex pattern described there might be explained by an analytic model, in terms of a simple dynamical system, with few assumptions concerning motivation and learning. The model is studied both by analysis and simulation. The theoretical examination of the dynamics of excursion length suggests that excursion length increases as a linear function of two system parameters, one governing the rate of motivation loss, and the other the rate of (location-specific) familiarization. Combining this theoretical finding with the empirical results suggests that the two theoretical parameters are linearly related: the less confident the rat, the slower its familiarization rate, and thus differences in patterns of movement between rats can be explained using one rat-specific parameter. Furthermore, the more complex velocity pattern of the rat can then be easily captured by the same model. The analyzed behavior of the rat suggests that the locale sensory information that the rat collects has a gradient towards the home base, with decreasing information input away from home base. This sensory pattern emerges from the simple set of rules and restrictions on the rat's exploratory behavior. Thus, instead of imposing a set of ad hoc restrictions on a simulated rat so that its spatial learning is similar to that of a real rat, the model suggests a set of simple intrinsic constraints to govern the exploratory behavior.

1 Introduction

Students of exploratory behavior traditionally examine spatial learning in the context of predefined tasks (Berlyne 1960; Mittelstaedt and Mittelstaedt 1980; Olton et al. 1979; Whishaw and Mittelman 1986) or of spatial representation (Gallistel 1990; Muller et al. 1990; O'Keefe and Nadel 1977; Poucet 1993; Tolman 1932). In these studies, specific aspects of the exploratory behavior are studied only as to their effect on the completion of the tasks in question. Thus, the higher level tasks lead mostly to the understanding of fragmented aspects of the lower level exploratory behavior and have limited bearing on the understanding of the natural (unrestrained) exploratory process. For students of robotics who simulate spatial learning, however, the natural 'low level' exploratory kinematics are the first step upon which the higher order learning process is organized (Brooks 1994; Mataric 1991; Nehmzov and Smithers 1991). To establish a common language between both groups, a simple analytical model is suggested here that captures to a large extent the kinematic structure of rat exploratory behavior:

In a previous study, we suggested a method for a dynamic representation of free spatial behavior in the rat (Tchernichovski and Golani 1995). In the first part of the present study, we used this method to analyze the progression of the exploratory process from moment to moment. The quantitative analysis uncovered a stable pattern in the complex kinematics of exploration (see details in next section). With this pattern, we now suggest a model for the interaction of the rat with the environment during exploratory behavior, by which some of the complexity of the moment to moment kinematics can be derived from a few assumptions. This is achieved by formalizing the interaction of the rat with the novel

Correspondence to: O. Tchernichovski
(e-mail: ilan99@ccsg.tau.ac.il,
Tel.: +972-3-6409391, Fax: +972-3-6409403)

Present address: The Rockefeller University Field Research Center, Tyrrel Rd, Millbrook, NY 12545, USA

environment in terms of a dynamical system, such that the dynamics of the proposed 'intrinsic forces' determine the momentary location and velocity of a simulated rat. Such forces or higher level variables are introduced only to the extent that they are necessary for recovering the kinematics. We use terms such as motivation, familiarization, etc. in their loose sense for the proposed higher level functions, only as names for our proposed variables. The model is studied both by analysis and by simulation, and the predictions of the model are juxtaposed with experimental results of spontaneous exploration in rats. Our results provide new insight into the process by which the locale sensory information is presumably collected and organized. Yet, this process emerges from the simple set of rules and restrictions applied by the model to the rats' exploratory behavior. Thus, instead of imposing on a simulated rat a set of ad hoc restrictions so that its spatial learning is similar to that of a real one, the model suggests a set of simple intrinsic constraints to govern exploratory behavior.

2 The natural morphology of rat exploration

Rat exploratory behavior consists of regular excursions into the environment from a preferred place termed a home base (Eilam and Golani 1989). In young rats, the establishment of a home base is a unique event of transition from low and constrained activity in locale space to a diverse and free movement pattern (Tchernichovski et al. 1996). This suggests that home base behavior is involved in the process of spatial learning. The home base has been shown to attract the rat during its excursions into the environment in the following sense: as the rat leaves the home base, its probability of performing the next stop at the home base, thus terminating the excursion, increases first slowly and then quickly with every additional stop it performs. This process of increasing home base attraction suggests a cumulative process that is reset once the rat visits the home base (Golani et al. 1993).

In part I we described the progression of the exploratory process during and across consecutive sessions (observations) in the same large environment. We found that excursion length (the maximal distance travelled from the home base) increases during and across sessions. Each rat has its own characteristic length of excursions, but the slopes of excursion growth are similar across rats. We also found that the rat's velocity in any one place is related to the movement direction relative to the home base: initially, the rat progresses slowly and intermittently away from base (upstream velocity pattern) and fast and continuously back to the home base (downstream velocity pattern). The home base is thus 'attractive' to the rat. This pattern gradually changes, and after several excursions the home base becomes 'repulsive' in places which are proximal to it, in the sense that the asymmetry of the velocity pattern is reversed: the velocity on the way out becomes faster, and the velocity on the way back becomes relatively slow. The

transition from home base attraction to home base repulsion progresses proximodistally from the home base direction outwards, in correspondence with the familiarization process. According to this measure, the ratio between the distances of the familiar and unfamiliar places increases during exposure, at a rate which is similar among rats.

3 The model

We represent only the angular component of the rat's location (which moves in this experiment mostly near the walls) and use discrete steps, so that $x \in Z$ denotes a location in the field with 0 being the home base. We also use a discrete time frame $i = 0, 1, 2, \ldots$ denoting the stages at which the system is observed. We then endow each place with a potential value representing the 'level of uncertainty' (or fear) of a rat while visiting this place. In our experimental setup, the home base is an unique familiar hiding place. We therefore assume that initially the level of uncertainty of the rat associated with places further away from the familiar home base is higher than in the places closer to home base. This can be modelled by a symmetric potential field about a single minimum potential center. In stage i, the potential at x is $P_i(x)$. The difference in potentials between this location and the next inward neighbor is:

For $i > 0$

$$W_i(x) = \begin{cases} P_i(x) - P_i(x-1) & \text{for } x > 0 \\ P_i(x) - P_i(x+1) & \text{for } x < 0 \end{cases} \tag{1}$$

For ease of notation, we assume $W_0 = 0$ so that now

$$P_i(x) = \sum_{y=0}^{x} W_i(y)$$

both for negative and positive x's. We require $W_0(x) > 0$ for all $x \neq 0$ so that $P_0(x)$ increases with $|x|$ (which for simplicity we take here as $W_0(x) \equiv 1$). We consider a simulated rat (Sim-rat) loaded with a tendency (for convenience, we will use the term motivation) to 'climb' up the potential field. At stage i, the motivation level of the Sim-rat is M_i, its location is x_i, and the potential at its current location is $P_i(x_i)$. The Sim-rat 'observes' the potential field at this and adjacent locations: At any location of the Sim-rat, the two neighboring locations are denoted as:

$$\text{Up}(x_i) = x_i + \text{sign}(x_i)$$
$$\text{Down}(x_i) = x_i - \text{sign}(x_i) \tag{2}$$

At stage i, the Sim-rat moves to location x_{i+1} according to the following rule:

$$x_{i+1} = \begin{cases} \text{Up}(x_i) & \text{if } M_i > 0 \\ \text{Down}(x_i) & \text{if } M_i \leq 0 \end{cases} \tag{3}$$

so that while the Sim-rat is loaded with motivation, it moves uphill, from the home base outwards, and when it is depleted, it moves toward the location with lower potential. We assume further that each time the Sim-rat visits a place with a positive motivation, this place becomes more familiar in the sense that the potential difference over which it traverses is smaller (so that the next visit to the same place will induce less uncertainty in the Sim-rat). The interaction of the Sim-rat with the field is therefore described as follows:

$$W_{i+1}(x) = \begin{cases} W_i(x) & \text{for } x \neq x_{i+1} \\ \alpha W_i(x) & \text{for } x = x_{i+1} = \text{Up}(x_i) \end{cases} \quad (4)$$

where α is the proportion of the potential difference decrease during a visit.

Note: We can also assume that the rat increases its familiarity with a location on its way back – where the motivation is 0. This will not change the following results and discussion, except for a change from α to α^2.

The final component of the model describes the changes in the motivation as the Sim-rat moves in the potential field. We assume that moving up the potential field consumes motivation in proportion to the potential difference traversed. In contrast, the Sim-rat is reloaded with motivation at the home base. This is formulated as follows:

$$M_{i+1} = \begin{cases} M_i - \beta W_i(x_i) & \text{for } x_{i+1} = \text{Up}(x_i) \\ M_i & \text{for } x_{i+1} = \text{Down}(x_i) \\ 1 & \text{for } x_{i+1} = 0 \end{cases} \quad (5)$$

where β is the proportion of the Sim-rat motivation which decreases as the Sim-rat moves uphill. When $M_i = 0$, the Sim-rat moves (passively) toward the field center, where it is loaded with motivation and starts another 'excursion'.

To summarize the model so far: The two principal components governing the excursion of the Sim-rat are the potential field which is transformed locally by the Sim-rat according to (4), governed by the parameter α; the Sim-rat motivation which is transformed according to (5) and governed by the parameter β, which determines the cost of climbing and therefore the amount of potential difference that the Sim-rat can overcome during an excursion. The Sim-rat's motivation oscillates once within each excursion. In contrast, the potential field decreases monotonically both within and across excursions. The shape of the potential field determines the pattern of the current excursion which, in turn, changes the shape of the potential field for the following excursion.

We next endow the Sim-rat with speed so that the implications from this model can be compared with the kinematic measures discussed in part I. Speed is assumed to decrease linearly in potential difference while the Sim-rat moves up the potential field (away from base), and to increase linearly in potential while the Sim-rat moves down the potential field, as in one of its simplest forms:

$$v_i(x_i) = \begin{cases} C - W_i(x_i) & \text{for } x_{i+1} = \text{Up}(x_i) \\ -W_i(x_i) & \text{for } x_{i+1} = \text{Down}(x_i) \end{cases} \quad (6)$$

where C is slightly larger than W_0. This gives us a positive velocity when the Sim-rat moves from the home base in any direction, and a negative velocity otherwise, according to our notations for upstream and downstream velocities in part I where v is defined as positive outwards and negative inwards. The Sim-rat can be described at stage i by its current location and velocity (x_i, v_i). From here onwards, we can treat the simulated sequence of data similarly to the kinematic analysis of rat exploratory behavior as described in part I.

4 Analysis of the simulated excursions of a Sim-rat

We simulated the exploratory behavior of a Sim-rat using the above model. The Sim-rat displays 'home base behavior': It oscillates continuously from the center of the field, back and forth. Therefore, its output could be divided into excursions – i.e., to the data stretches (x_i, v_i) between every two consecutive visits to the field center. Figure 1A presents two-phase planes of a real rat with their corresponding velocity profiles, and Fig. 1B presents four phase planes (Tchernichovski and Golani 1995) of typical excursions of the Sim-rat. Each phase plane displays the trajectory of the velocity vs the momentary location of the Sim-rat during an excursion. It is evident that excursion length increases as a function of the excursion number. The movement pattern of the Sim-rat changes concurrently with increases in excursion length: In the first ones, which are short, the movement pattern indicates home base attraction; for every location visited by the Sim-rat, the speed is higher on the way back to the home base. This pattern is typical of early excursions in real rats (Fig. 1A left). During later excursions, the Sim-rat leaves the home base at high speed, then the velocity decreases until it starts its return. While returning, the speed is initially high, but when the Sim-rat approaches the home base, its speed decreases again (Fig. 1A right). Therefore, the movement pattern of the Sim-rat is reversed (becomes higher on the way out) in the vicinity of the home base. There, the velocity pattern falls into the category of home base repulsion pattern – it is higher on the way out. In the distant portion of each excursion, the velocity pattern remains primitive, i.e., it is higher on the way back. Both the change in excursion lengths as exploration progresses and the change in kinematics described above are qualitatively similar to the main findings observed in real rats.

In part I we further analyzed the movement pattern of the rat using two measures, AD and RD. For the locations visited during an excursion, each location was classified as 'home base attractive' or 'home base repulsive', depending on whether the speed on the way out was lower than the speed on the way in or vice versa. The average distance of home base attractive places is the measure AD and the average distance of home base
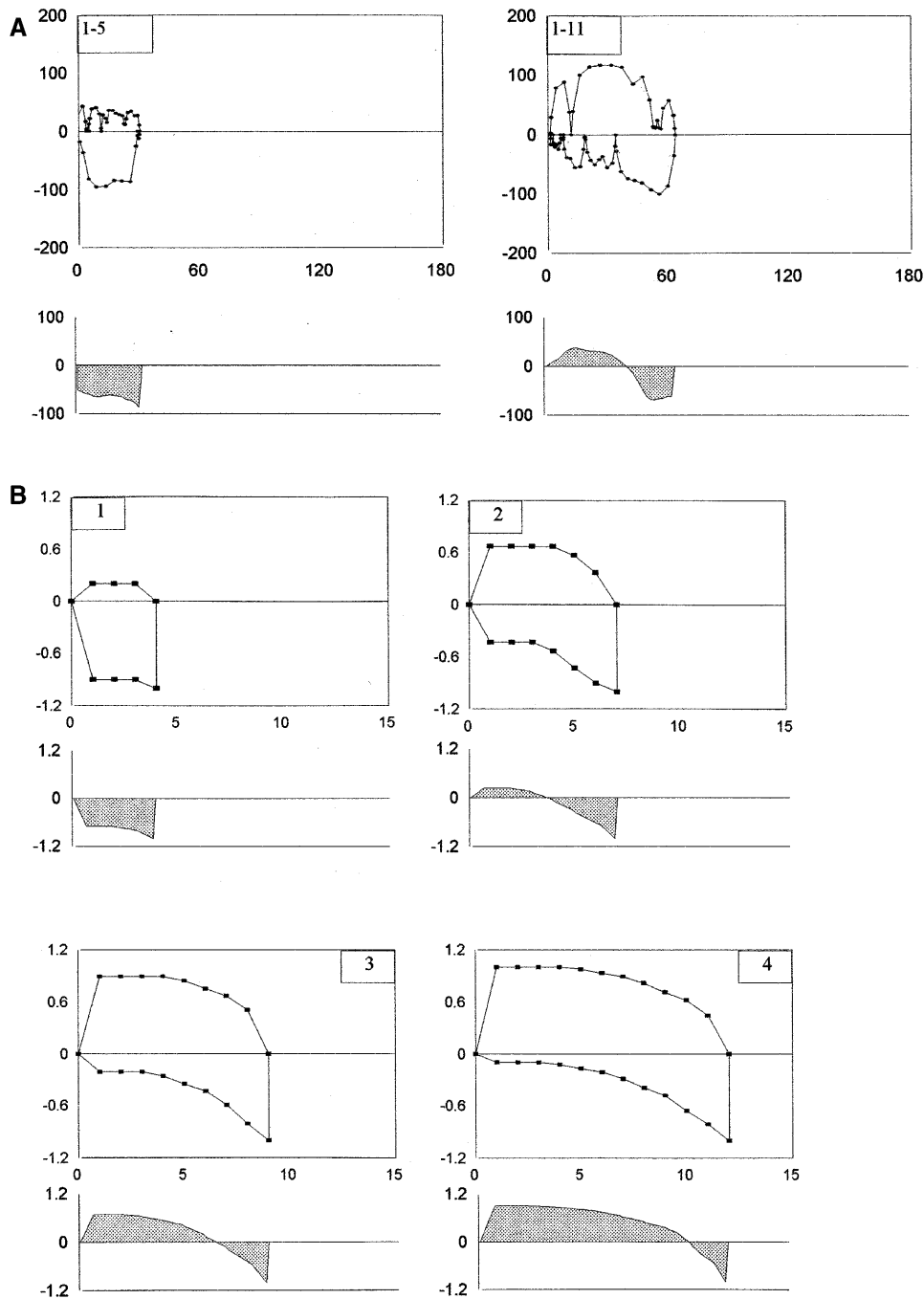
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Fig. 1A Two examples of phase plane representations, of the 5th and 11th excursions of the first session of a real rat. The *x*-axis represents angular location in degrees, and the *y*-axis velocity in cm/s. The graph below each phase plane represents the Velocity profile (V_p) of the excursion plotted in that phase plane. In the V_p graphs, the *x*-axis represents angular location in degrees, and the *y*-axis the algebraic summation of inward and outward speed. **B** Phase plane and corresponding V_p graphs of four excursions, at the beginning (excursion 1), middle (excursions 10, 20), and advanced (30) stages of the simulation. Parameter values are $\alpha = 0.1, \beta = 0.9$

repulsive places is the measure RD. It has been shown that for real rats both AD and RD increase, but AD remains higher than RD.

These changes in the geometry of excursions are the result of the accumulated changes in the potential field. As shown on the left side of Fig. 2, the initial shape of the potential field is linear. As time progresses, the field is flattened but not equally at each point: The more distant the location from the field center, the later it is visited, and therefore the initially linear potential field becomes convex. With time, the field becomes practically flat, within an extended segment around the field center. Visits to these places reduce uncertainty in the Sim-rat, i.e., these places become almost equally 'safe'. This

prediction of the model is supported by the experimental results: One of the most prominent properties of the home base is that it is preferred in time (Eilam and Golani 1989). In the right side of Fig. 2, we present the distribution of activity of a (real) rat in places according to their distance from the home base during different stages of exposure. As shown, the distribution of activity during the first exposure to the environment is strongly biased to the home base. As exposure increases, the activity of the rat spreads, but it is still centered around the home base area, although the exact location of the home base is not preferred. This experimental result was observed in all rats and supports the prediction of this model.

5 A theoretical examination of the model

The previous results were based on the simulated behavior of the Sim-rat according to the model. We will now examine the model in terms of the analytical derivations of the behavior previously discussed, namely AD, RD, and excursion length. While the analysis of the first two is much as expected, the findings regarding excursion length are more thought-provoking.

5.1 A theoretical examination of AD and RD

Let the location of maximal distance from the home base travelled by the Sim-rat at the jth excursion be denoted by D_j for $j = 1, 2, \ldots, n$. Define the potential at D_j at the beginning of the jth excursion as $P_j(D_j)$. Because of the relationship in (6), $RD_{(j)}$ is the average of all x's such that $W_j(x) < 0.5$ and $AD_{(j)}$ is the average of all x's such that $W_j(x) > 0.5$. Since a rat cannot visit a location x without first passing all $0 < y < x$, $W_j(x)$ is monotonically increasing in x. Therefore, there exists a single x_j^* such that $RD_{(j)}$ is the average of $1, 2, \ldots, x_j^*$, which is $(x_j^* + 1)/2$, and $AD_{(j)}$ is the average of $x_j^* + 1, x_j^* + 2, \ldots, D_j$, which is $(x_j^* + 1 + D_j)/2$. Therefore, $AD_{(j)} = RD_{(j)} + D_j/2$, and obviously $AD_{(j)} > RD_{(j)}$. Since $W_{j+1}(x) \leq W_j(x)$, $x_{j+1}^* > x_j^*$ and so $RD_{(j+1)} > RD_{(j)}$. Furthermore, since $P_{j+1}D_j < 1$, $D_{j+1} \geq D_j$, we also have $AD_{(j+1)} \geq AD_{(j)}$ (an explicit expression for D_j is developed in the next section). Thus, the characteristics of both RD and AD have been derived analytically from the model.

5.2 A theoretical examination of excursion length

We will now examine the excursion length of the Sim-rat as a function of the temporal sequence of excursions
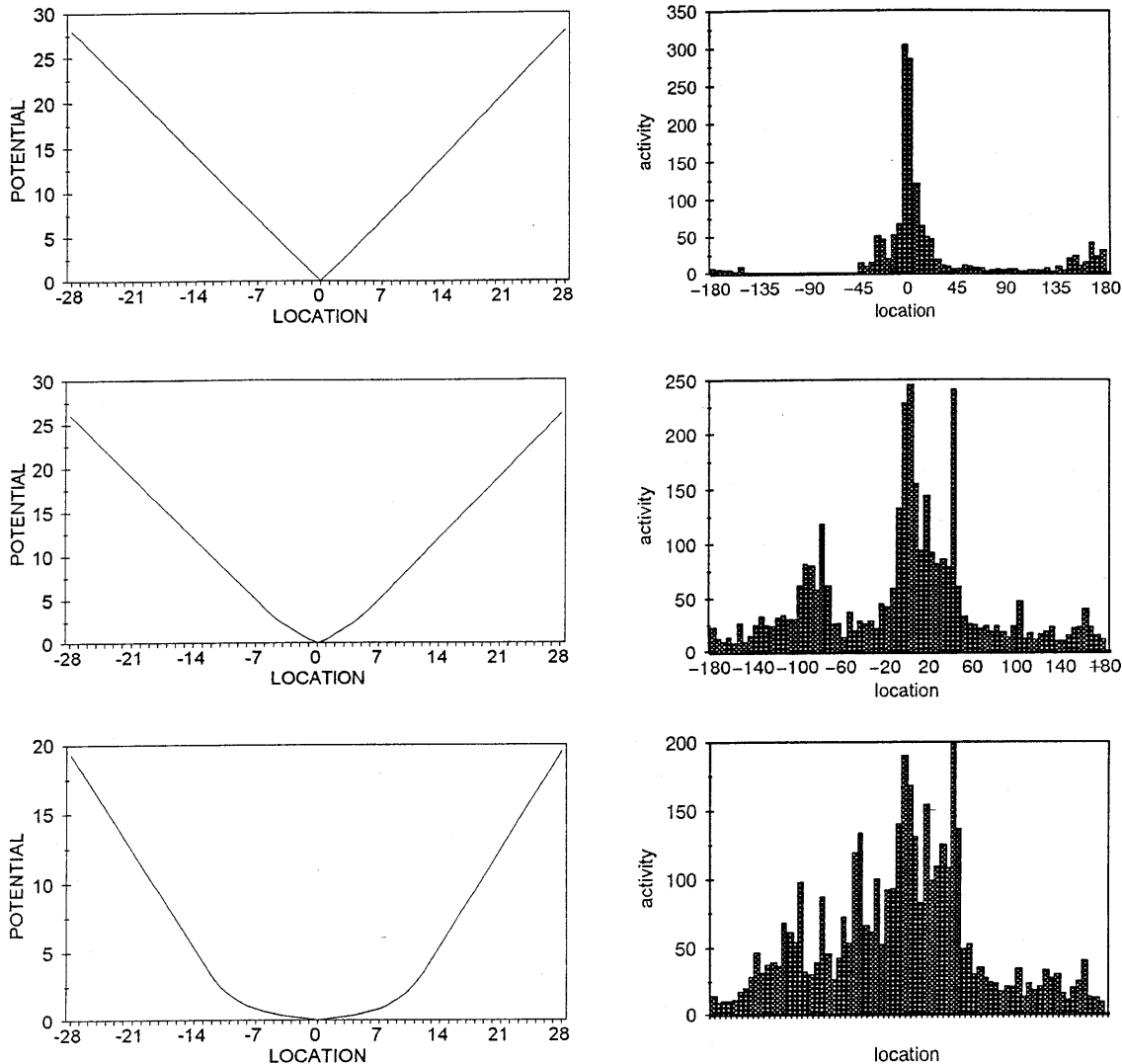

Fig. 2. On the *left side, from top to bottom*, the shape of the potential field at different stages of the model simulation. On the *right*, the distribution of activity of a real, specific rat in local space for its first, fourth, and sixth sessions. Each *bar* presents the cumulative number of movement records collected by an automatic tracking system in every location extending over an angular interval of 5°. Each graph presents the cumulative data per session

(time). In practice, the Sim-rat moves in both directions, but for the sake of simplicity of proof, we will assume that the consecutive excursions are all in the same direction. Little is lost, because of the symmetrical treatment of both directions. The initial motivation of the Sim-rat at the beginning of excursion j is unity by definition, and from definition of D_j

$$\beta P_j(D_j) = 1 \tag{7}$$

According to (4), by the end of the same excursion, the potential at D_j is:

$$P_{j+1}(D_j) = \alpha P_j(D_j) \tag{8}$$

and obviously $P_{j+1}(D_j) < 1$.

In the next excursion, while moving from the field center to D_j, the Sim-rat will lose $\beta P_{j+1}(D_j)$ of motivation and will then be left with $1 - \beta P_{j+1}(D_j)$ of motivation to move further up the potential, and therefore the next excursion will be longer than the former by:

$$D_{j+1} - D_j = (1 - \beta P_{j+1}(D_j))/\beta W_0 = (1 - \alpha \beta P_j(D_j))/\beta W_0$$

According to (7), $\beta P_j(D_j) = 1$ and therefore:

$$D_{j+1} - D_j = (1 - \alpha)/\beta W_0 \tag{9}$$

Note that the right side of (9) does not contain j and is therefore a constant. Thus, excursion length is a linear function of the excursion number, and is given by:

$$D_j = 1/\beta W_0 + (j - 1)(1 - \alpha)/\beta W_0 \tag{10}$$

Adhering to our convention to let $W_0 = 1$:

$$D_j = 1/\beta + (j - 1)(1 - \alpha)/\beta \tag{11}$$

or, in terms of j

$$D_j = (\alpha + (1 - \alpha)j)/\beta$$

6 The implications of the empirical findings within the theoretical framework

In this section, we make use of the empirical findings in part I. When these findings are embedded in the linear growth of excursion length derived theoretically above, new constraints emerge regarding the values of the parameters in the model. Such use of the empirical findings within the theoretical framework should be made with caution since (i) rat data are very noisy, while the model does not contain a stochastic component, (ii) data analysis was performed using session stages as the units of analysis rather than the sequence of excursions length. We will thus proceed with due caution. In part I, we found a significant difference in excursion length among rats. In addition, we found a significant increase in excursion length during exposure, but this effect was similar among rats. In terms of the model, this means that the intercept $1/\beta$ is variable among rats, while the slope $(1 - \alpha)/\beta$ is similar among rats. Since the slope is similar among rats, we have:

$$K = (1 - \alpha_r)/\beta_r \tag{12}$$

where the notation r means that both α and β might be variable among rats, but K is similar among rats. If we want the intercept $(1/\beta)$ to be variable, then β must be variable, but β is also the denominator of (12). Therefore, α must also be variable among rats since $K\beta_r = 1 - \alpha_r$. We may therefore conclude that (i) both α and β vary among rats, and (ii) there is a decreasing linear relation between β – which governs the rate of motivation loss – and α – which governs the rate of familiarization. In other words, rats that are 'cowardly' familiarize more slowly: Their excursions are shorter and the rate of flattening of the field is lower. The differences in excursion length change over time between rats can therefore be explained by one degree of freedom, e.g.:

$$D_j = \beta_r^{-1} + K(j - 1) \tag{13}$$

This linear relation between the uncertainty of a rat and its familiarization rate might be explained on the kinematic level: Previous studies showed that stress has a direct effect on the repertoire of exploratory movements that a rat might perform (Golani 1992). It might therefore be possible to measure β as a kinematic variable.

7 Discussion

7.1 The integration of spatial memory

The findings of part I and the current model reveal a location-specific familiarization process that advances during each visit to a location. Like Poucet (1993), we assume that the rat memorizes part of the locale sensory view at each visited place. Under this assumption, the movement pattern of the rat will have a major influence on its accumulated database: If a rat explores the environment at random, it would end up with a large table of places with a homogeneous level of information on all places, but in which the amount of information collected in each place might be low. The rat, however, moves around a home base and visits the same places again and again, while novel places are gradually added to the familiar path. This pattern of movement would lead to a database of rich information on places which are in the vicinity of the home base, and these places would tend to be clustered. Rich information on a group of neighboring places would obviously have a large overlap. Such a database (i) is convenient for the integration of spatial information; (ii) allows a rapid establishment of a familiar area in a hostile environment; (iii) contains a radial gradient of decreasing level of familiarization around the home base; and (iv) accumulates information smoothly.

7.2 Motivation

The exploration process described in part I and modeled in this part shows several similarities to the searching

behavior of homing ants, desert isopodes, and funnel-web spiders (see Sect. 4.5, part I). From the Mittelstaedt navigational model, as described in Mittelstaedt (1985, p. 314, Fig. 11), it can be inferred that the homing spiders move home with a speed depending linearly on the distance from home. An equivalent of the envisaged 'motivation' parameter may be found in the theory of optimal search developed by Hoffmann (1983a,b, 1978). Finally, the structure of the analytic model for the exploration process described here is also very close to the structure of the model suggested by Wehner and Srinivasan (1981) for the search process of the homing ant when it is lost on the way back to the nest.

First, we identify the search for the nest as the motivation causing the rat to leave the place of initiation of the search – the home base. Our potential field of unfamiliarity, which is associated with each location, takes in the ant model the form of (minus) the likelihood of the nest being at that location. This function has a minimum at the search initiation point and increases as the distance from the point of minimum increases. Furthermore, the ant is assumed to perceive this likelihood, which in turn determines whether the movement for search is directed away from the center or inwards. Finally, each visit to a location lowers the (minus) likelihood of the nest being there. Thus, we claim that the search model can be embedded within the model presented here (aside from our model being one-dimensional), when the terms take their appropriate but different interpretations. Note that in a later work, Muller and Wehner (1994) have taken the optimal search property as the sole driving force which predicts the formation of spirals. Yet in order to produce the loops of increasing length observed in the ant, they assume the failure of the path integration system of the ant, and need to go back to the initial location. No such failure can explain the similar phenomenon observed in the rat, and the need to return is unexplained. Thus, the current model is more in accordance with the original search model of Wehner and Srinivasan (1981), rather than the later one. Recall from the discussion in part I that although the ant's behavior can be explained by optimal search, it can also be argued that the more general concept of exploration in an unfamiliar area – which is the situation the animal is in when it is lost – is appropriate by itself. As suggested in part I, an experimental test for such a claim would involve moving both ant and nest to a novel environment, where exploration has to take place but no search for the nest is needed, and the pattern is still observed. It may be more fruitful, though, to leave the model in its generality, permitting different interpretations in the future. This may allow us to discover similar patterns of behavior in problems where neither search nor exploration take place, and a more general principle may be phrased in the future that will be able to explain both phenomena as well as others. Such a principle may be, for example, that movement develops along time by repeating the same basic scheme again and again, each time extending its reach further away from the starting point. A further reaching principle may be related to the properties of the preconfig-ured network that generates the abstract internal representation of two-dimensional space, and the associative learning of the connection between landmarks and the preconfigured path integrator which has been studied and described by McNaughton et al. (1996). It may be extremely satisfying, and exciting, if the pattern of behavior modeled here turns out in some way to be a desirable feature of efficient training of the relevant neural networks as described there.

7.3 Habituation

One major point in which the model is not realistic is that exploratory behavior of a real rat terminates spontaneously after awhile, a phenomenon termed habituation (Horn 1967). The Sim-rat does not habituate but continues to explore endlessly. At least in our experimental setup, habituation is a temporary termination and not a conclusion of the exploratory process, i.e., the rat typically explores only a part of the arena during one session, and as mentioned, the exploratory process progresses in future sessions. The model can capture habituation, however, by making β a time-dependent variable. Assuming, for example, that $\beta = 0.1 \times \text{EXP}(i/1000)$, the excursion length will first increase, but the rate of increase will eventually slow down. Since the field is flattened in a logarithmic rate and β increases exponentially, excursion length will at some point decrease until the movement dies. This might explain the nonlinear decline of the slope of excursion length toward the end of each session, with little influence on other properties of the model.

7.4 The exploratory process across sessions

The experimental results show that both excursion length, AD, and RD increase among sessions. These measures in fact typically drop at the beginning of each session from the highs of the preceeding session but then increase, reaching in most cases higher values than the maximum of the preceding session. Our assumption of additive flattening of the potential field does not explain such findings. Moreover, careful observation reveals similar phenomena also within sessions: For example, if a rat performs several excursions to the left between two consecutive excursions to the right, we frequently observe a drop in the measurements of the second excursion to the right compared with the first. These findings suggest that a more realistic model might include the flattening of the potential field as a time-dependent decay function.

7.5 Other patterns that are not included in the model

We found that the length of a jth excursion depends on the length of the $j - 1$ excursion in the following nontrivial way: A long excursion is typically followed by a few short excursions. This dependency is another

source of noise that might be reduced by adjusting our assumption that the Sim-rat starts each excursion with a constant amount of motivation. In addition, the Sim-rat moves continuously, while the movement pattern of a real rat contains stops. A comprehensive model of home base behavior should include a stochastic component and should also explain the uniform distribution of stops per excursion reported earlier (Golani et al. 1993).

A critical question is to what extent might the observed kinematics (and the validity of the model) be restricted to the current testing environment? According to the model, the integration of spatial memory is related to the tendency of the rat to explore the arena back and forth through the same route. This tendency might be lower if, for example, the home base is located in the middle of a circular arena. Still, both in nature and in laboratory situations, rats tend to move along the boundaries of the environment, back and forth (typically around a corner), just as in the current setup.

This study is limited to exploratory behavior in reference to one predefined home base. Home base behavior was observed in a variety of environments, including a round arena that contains no shelter and rectangular arenas of different sizes (Eilam and Golani 1989; Golani et al. 1993). Yet, sooner or later, the establishment of additional preferred places was observed (Tchernichovski et al. 1996), even in the current setup that was planned to discourage such behavior. In fact, during advanced stages of exploration, many places in the arena act as 'field centers' in the sense that the rat performs fast and 'ballistic' trajectories toward them: Such trajectories were initially observed for distances of 20–80 cm but later to distances of 10–15 m. These preliminary findings raise interesting hypotheses about the presumed processes of increasing the 'connectivity' of locale space. The concept of integration of locale schemata (Arbib 1990; Poucet 1993) was suggested as an alternative to the traditional paradigm of global space representation (Gallistel 1990). A further kinematic analysis of long-term exploration, in a variety of environments, might uncover the establishment and the integration of such partial reference systems. Such analysis could lead to a more appropriate model.

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