Time and "home–range" borders in individual–based artificial–world modelling

Lorenz Gygax
Department of Applied Mathematics
University of Zürich-Irchel
Winterthurerstr. 190
CH-8057 Zürich / Switzerland
e-mail: lgygax@amath.unizh.ch

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Abstract

In a simple model where 5 animats move independently and randomly over a 10 by 20 lattice the influence of different approaches to modelling time and borders of the lattice on the use of the lattice and on the occurrence of meetings between animats is studied. The approaches of modelling time include a parallel regime, a regime with random waiting times till activation and one with random waiting times and local activation. Borders are modelled by a toroid shape of the lattice, a fixed border and behavioural reflection. The way the border is modelled influences the homogeneity with wich individual fields of the lattice are visited and how long meetings between animats last whereas the different approaches to model time lead to significant differences in the lenght of the meetings. These issues should be considered in discussions of individual–based artificial–world models and taken into consideration if building new models.

Keywords: individual–based modelling, artificial–world modelling, space, time, borders, home–range

Introduction

Models using differential, partial–differential and difference equations have long and widely been used in ecological research (e. g. Abrams, 1994; Akçakaya *et al.*, 1995; Holmes *et al.*, 1994; Goss *et al.*, 1989) and less often in behavioural research (e. g. Bonabeau *et al.*, 1996; Calenbuhr and Deneubourg, 1992). Recently these models have been extended to accomodate more details as in e. g. structured population models where one can model different subclasses of animals with each subclass having its own characteristics (e. g. DeAngelis and Godbout, 1991; Petersen and DeAngelis, 1992; de Roos, 1995). Another and even farther extension are the family of models introduced in ecological and behavioural research: the individual–based artificial–world models (Hogeweg and Hesper, 1990b; Judson, 1994; Hogeweg, 1989; Hogeweg and Hesper, 1979; Hemelrijk, 1996).

In these latter models individual animals ("animats") with a given behavioural mechanism move in a specified environment and base their actions on local information. These models have many advantages. Among them are: (1) The model input from data (behavioural mechanism and structure of the environment) is quite easily observable and on a different level than the phenomenon of interest in the model, such as habitat utilization, social structuring, population dynamics, and others; (2) Space is explicitely modelled and can thus possibly structure the behaviour (outcome) of the model; (3) The language to talk about the model and methods used for model evaluations are identical to those known from work with the real phenomenon.

Different modelers have used different approaches to model time and space (here I consider especially the boundaries of the model–space), but often fail to make it explicit how they go about it. A lack of standards in model presentation was recently formulated in Bart (1995).

Time is mostly modelled to be either synchronous, parallel, or pseudo–parallel. Synchronous means that all entities are updated together at certain times of the model–clock (e. g. Hogeweg, 1988; Wolff, 1994). This approach is most often used in models that are based on cellular automata. In parallel models the animats behave in parallel but not necessarily synchronous. Though very natural, these models are still quite rare as they are most easily implemented on parallel computers.

Pseudo–parallel (often called event–based) models (e. g. Lhotka, 1994) try to avoid the synchronisation of the first and the hard–ware dependence of the second method. One straightforward way to implement this is to give each animat a random waiting time and then deal with one animat at a time (the one with the currently shortes waiting time).

Some psudo–parallel models are extended to allow local activation. I. e. the waiting time of animats that are close to an active animat or a special location is reduced and thus the interval to the next activation shortened for this animal (e. g. Hogeweg and Hesper, 1983).

Most authors are more explicit about how they model space and the borders of the modelled home–range. Home–range in this paper is meant to describe the area where an animat can be found in the model landscape, which should reflect the area where an animal moves in the wild.

Space is most abstractly modelled as a regular lattice (e. g. Hogeweg, 1988; van der Laan *et al.*, 1995), similar as in cellular automata, or as a continous square or landscape (e. g. Liu, 1993). In both systems the borders may either be absent, i. e. the model space forms a toroid (e. g. Hemelrijk, 1996; Ruxton, 1996), fixed (e. g. Turner *et al.*, 1994) or avoided by a model mechanism, e. g. animats wander through the area which only represents a small part of the system of interest (e. g. Hogeweg and Hesper, 1990a), or animats are reflected at the boundary (e. g. Reuter and Breckling, 1994).

Sometimes patches of space are connected in a given way to form networks with only restricited accessibility from one patch to another (e. g. Hogeweg and Hesper, 1983; Folse *et al.*, 1989).

In other models the animats' dominante behavioural mechanism is to follow resources (females and/or food). They presumably stay within the home–range mainly because these resources are confined to it (te Boekhorst and Hogeweg, 1994b,a) though the authors don't state the mechanism explicitely.

In this study the influnece of the timing regime (synchronous, pseudo–parallel and pseudo–parallel with local activation) and border rules (toroid, fixed border and behavioural reflection) on the visits to fields of a lattice and on the number of encounters between animats is studied in a quantitative way.

Methods

Computer simualtions for this study have been conducted using C^{++} with the GNU compiler g++ on an aix 6000 cluster. The language was chosen because it includes object–oriented features (Haltermann, 1995; Silvert, 1993) which help in individual–based artificial–world models (e. g. Liu, 1993; Galea *et al.*, 1996) but is more widely available than other more specialized object–oriented languages such as e. g. SmallTalk (Baveco and Lingeman, 1992; Lhotka, 1994; Baveco and Smeulders, 1994). Another advantage is that it is a truly compilable (and not an interpreted) language and thus the simulations run very fast.

The code for the present simulations has not been speed optimized as the models were already very fast if compiled with `g++ XY.cc -o XY.out` and run with `time XY.out` > `XY.runNO` (where `XY` is the name of the specific program [a specific time–border combination] with a specific random seed and `NO` is the run number).

The programs all consisted of the `ran2` random-number generator suggested in Press *et al.* (1992) (the seed was taken from the uniform random number generator in S–plus, see section on statistics), a definition of the class "animat" and its methods and the function `main ()` which initalized the position of the animats and updated their position a certain number of times or during a certain time (measured by the model–clock, see below). At each point in time when an animat moved the time and the position of each animat were written to standard out (and redirected to a file).

In the present simualtion runs five animats moved independently on a lattice of size 20 by 10. At each time when they moved they chose to do one step north, south, east or west according to given probabilities (see below). The model time would run from 0 to 2000 (see below).

Modelling time

Parallel: After the random initializaiton of the position of the animats, they all synchronously moved 2000 times.

Pseudo–parallel (random waiting time): With each move the animats were assigned a unifom random waiting time between 0.5 and 1.5, then the animat with the shortest waiting time was chosen and moved, all the waiting times and the model–clock updated. This was repeated until the model clock reached the value of 2000.

Pseudo–parallel with local activation: As in the pseudo–parallel case with the addition that the waiting time of animats that were in the vicinity (not farther than a distance of 2 away from the new location) of an active (moving) animat were drastically reduced (by a factor of 0.25).

Modelling borders

Toroid: The animats move on the lattice as if it was a toroid.

Fixed border: The animats move along the edge and back into the field with equal probability if they are right at the edge of the lattice.

Behavioural reflection: As in the fixed border condition, but the tendency to move along the edge or back into the field rather than further towards the edge decreases from the third field from the edge. The probabilites to move further towards the edge are for the four outmost rows: 0.25, 0.22, 0.16 and 0, i. e. the tendency not to go further is getting larger step by step.

Response variables

To judge the differeneces in the model outcome caused by the different approaches to modelling time and borders the following response variables (observed behaviour of the system) were evaluated for one animat per run. All variables were chosen to be interpretable in a biological context of habitat utilization and/or social interaction.

Median values and inter–quartile ranges (IQR) were preferred over mean and variances and are reported here. The preference was due to their robustness towards outliers their being typical in the sense that the values represent fix quantile–points/–intervals in the distribution of the data. Some of the response variables were also evaluated by their means and variances and the qualitative results were the same. This is to be expected as the response variables are not expected to deviate greatly from a specific (?) distribution, as the whole model only includes "random processes".?

Number of moves: Number of times the animat in focus moved during the model run.

Median number of visits to each field of the lattice as a measure of how uniformly the field was used (combined with the IQR, see next item).

IQR of the number of visits to each field

Median number of visits to the fields at the oumost edge to get a more specific idea on how the border condition influences the use of the fields towards the edge (combined with IQR, see next item).

IQR of the number of visits to the border fields

Number of fields with no visits The number of fields that were not visited at all.

Median number of meetings The median of the number of times the animat in focus was closer than 2 fields from the other 4 animats. To count as a new meeting the two animats concerned had to be farther apart for at least one step of the model–clock.

Range of number of meetings Maximum number of meetings minus mimimum number of meetings with the 4 other animats.

Median length of meetings Median length of meetings with one other animat (in units of the model–clock).

IQR of length of meetings

Additionally the size of the record file (including the time and the location of all animats at all the times when at least one of the animals has moved) and the UNIX real, user and system time (output from the UNIX comman `time`) were recorded (see Discussion).

Statistical analysis

The simulation output was evaluated using S–plus (Becker *et al.*, 1988; Chambers and Hastie, 1992; Venables and Rippley, 1994) Version 3.2 on a Sun 2 with 36 MB RAM. The response variables were singly tested in a two–way ANOVA with the different time and border conditions as explanatory variables.

A full model with the interaction was calculated and then a stepwise–backwards procedure was used to eliminate insignificant varibles. Some response variables were square–root transformed to achieve a better normal distribution of the residuals (see Results).

Residuals of the ANOVA were checked for normality, expected mean of zero and constancy/equality of variance using graphical methods: the qqnorm–plot (residuals versus quantiles of a normal distribution), the Tukey–Anscombe–plot (residuals versus fitted values) and plots of the residuals versus the explanatory variables.

Some response variables showed a long–tailed distribution (a distribution with outliers). It is not clear why these occurred as the model was a model of pure random walk. Nevertheless, in the case of outliers, the statistical model was recalculated without the outliers (Table 1).

Results

All the response variables could be transformed so that the assumption of normally distributed errors was not seriously violated (Table 1). A typical residual plot can be found in Fig. 1. In these plots the line in the qq–norm plot might show small steps due to the response variables being counts, the variation of the residuals sometimes are slightly different between the groups. In some response variables outliers had to be excluded from the analysis, but the significance of the explanatory variables remained the same.

The number of moves was mainly influenced by the variable time: the parallel movement of the animats and the assignement of random waiting times between 0.5 and 1.5 time–lengths had both fewer movements (exactly 2000 for the parallel case and a median of 2004 for the random case) than had the conditions where there was an aditional local activation (median number of moves 2286.5, Fig. 2, top). After eliminating the ouliers, the number of moves also showed dependence on the way the border was modelled and on the interaction term between between time and border (Table 1). These latter are not obvious in the plot but might be due to small differences in location combined with a rather small variance of the distribution of the number of moves. These results make it necessary to correct some of the subsequent response variables, i. e. they were divided by the number of moves.

The median number of visits to the fields corrected by the number of moves showed a decrease from the toroid to the fixed border and the behavioural reflection (Fig. 2, middle).

The IQR of the number of visits to the fields was not corrected because even if the median number increases with the number of moves, the IQR would not necessarily behave in the same way (the qualitative outcome with the correction is the same). The IQR gets higher from the toroid to the fixed border to the behavioural reflection (Fig. 2, bottom and Table 1).

The median number of visits to the fields on the outmost edge of the lattice corrected for the number of moves were highest for the toroid intermediate for the fixed border and lowest for the behavioural reflection (Fig. 3, top and Table 1). The IQR of the number of visits to the fields on the outmost edge of the lattice was also highest for the toroid, slightly lower for the fixed border and lowest for the behavioural reflection (Fig. 3, second from top and Table 1) wheras the IQR corrected for the number of moves showed the inverse pattern (Fig. 3, second from bottom and Table 1). The number of fields with no visits corrected with the number of moves showed this latter pattern, as well. Additionally there were slightly more fields with no visits in the parallel and random than in the local activation (Fig. 3, bottom and Table 1).

The median number of meetings corrected by the number of moves showed no change between the different modelling approaches (Fig. 4, top and Table 1). The toroid situation showed a decreased range of the number of meetings (corrected by the number of moves) in comparison to the other two approaches (Fig. 4, second form top, Table 1). The median length of meetings decreased from the parallel to the random to the local activation and the IQR of the length of the meetings showed a parallel pattern (Fig. 4, bottom two, Table 1).

Discussion

These model runs show, that even simple changes in the manner of how to compute time and borders in an individual–based artificial–world model lead to different behaviour of its inhabitants and it is thus important to report these mechanism so that other researchers can view the results of the simulations in the light of the approaches used (Bart, 1995).

In these models an increasingly complicated way to model time (from parallel to random to local activation) lead to shorter meetings and such with less variable length. The IQR might just be correlated with the length of the meetings. In the parallel case all the meetings last at least 1 time–step whereas in the other two situations many meetings will be shorter: one animat moves into the vicinity of another and then it or the other moves away at the next activation time which can be shorter than 1 time–step. It is astonishing though, that with the random activation (with or without the added local one) one can not observe more meetings per number of moves than in the parallel case. On the other hand the range (and with it the maximum length of the meetings) increased the more complicated the border is modelled (from toroid to the fixed border to behavioural reflection). This is probably a consequence of the more restricted directions to move at the edges of the lattice, so that animats close to the border are more likely to stay in each others proximity.

The increase in complexity of the approach to model the border also leads to a lower median number and a higher IQR of visits to the fields, a lower median number of visits and a lower IQR of visits to the fields on the edge of the lattice and to an increase in the number of fields with no visits. This can all be explained with the fact that the animats are more seldom in the fields on the edge of the lattice.

These variables have to be considered if looking at applications of such models. It means that depending on the modelling approach animats use their modelled habitat more or less homogenously and that the chances for interactions between animats might differ. If the phenomenon under study is very robust it can still appear independently on the basic approaches to model e. g. time and border through the simulation that runs on top of these "low–level" problems.

Another important ascpect in these models is how much computer resources are used. The size of the output file (about 5 to 35 KB) depended mainly on the way time was modelled. This is obvious as the location of animats was written to the file whenever one of the animats was acitvated. This is not necessary in every case; it could be enough to write the new position of the animat that has moved. Output might be much further reduced if part of the evaluations were conducted within the program. More interesting is the run time of the C^{++} programs. Real (about 0.5 to 14 sec) and user time (about 0.5 to 5 sec) showed many large outliers in comparison to the system time (about 0.01 to 0.18 sec). Nevertheless, all showed the same qualitative behavior: The runs with local activation used slightly more computer time than the ones with random activation and both needed clearly more than the parallel activation. The case of local activation on the toroid used the most memory as the calculation of the neighbourhood on the toroid obviously used more memory than the different styles to model the borders.

In deciding how to model time and borders in a specific simulations it is thus important to consider the naturality of the approach, the ease of computing and necessary assumptions about the behavioural mechanisms.

Animals in nature certainly behave in parallel to each other. In this respect, the parallel approach to modelling time seems to be the most natural. On the other hand it is very rare that animals in nature move exactly at the same time. Thus the naturalistic way to model time might be to take very small steps in time but not moving (or not letting) the animat (behave) most of the time steps. This is then closely approached with the assignement of random waiting times to each animat but without the waste of a lot of model time at which nothing happens. On top, it is not farfetched to assume that an animal reacts more quickly to something important going on in its vicinity which can be reflected with activating animals locally. The only possible disadvantage of the local activation is, that animats that are close to others already, start to dominate what is happening in the model and thus other animats might have a decreased probability to get into the vicinity of another animat.

The truly parallel approach has another limitation: if one wants to add more complex social interactions then one has to make strong assumptions about the animats mechanism to forsee another animats trajectory as not to overshoot in an approach. Additionally, in a model with parallel activation the model state always changes between two time steps: the past one on which the decisions to move were based and the recent one reflecting the present situation. In models with random activation there is only the present on which the animat with the shortes waiting time makes its decisions, moves (behaves) and leaves a present state for the next animat in turn. Thus one could say that the local activation is a rather easily computed way to achieve a naturally behaving system without detailed preassumptions on the animtes behavioural mechanisms.

The toroid is certainly the simplest way to model a lattice but also the most unnatural (how many beings live on a toroid?, except maybe Escher's ants [or was that a Moebius–band?]). Additionally, one avoids a first, very simple structuring of the space which can have a huge impact on the behaviour of a model–system. The alternatives presented here are certainly simplistic be it the fixed border or the somewhat more continous behavioural reflection. The disadvantage of such approaches is again, that they make strong assumptions on behavioural mechanisms of the animats. Thus the recommendation here might be try to avoid borders that must explicitely be modeled. This can be achieved in different ways: either one has a network of patches where only certain moves are possible anyway, one lets the animats go through a lattice and they just disappear if they go over the edge or the behavioural mechanism of the animats if it is somewhat more complicates might be focused on resources that are only available within the boundary of the model–lattice, such that most decisions lead to moves within the lattice anyway. If the borders are small compared to the rest of the lattice the problem of what happens at the border is less and less an issue.

In the present paper the influece on the model outcome in individual–based artificial–world models was only investigated for two possible variables. It is obvious that other variables might also influence the outcome and obscure "low level" decsions such as how to model time and borders. Such variables might inlcude in increasing order of complexity: continuous space instead of discrete space, variable step size (either random or controlled through the local environment), more variable step direction or directional movements, the perceptive field of the animat, the shape and strucutre of the landscape and more complex behaviour of the animats, which is, of course, what we are finally interested in.

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Table 1: Outcome of the statistical analysis (ANOVA). All models reported were significant with at least $p < 0.01$. Given are the response variable, whether the response variable has been transformed (c: corrected values, i. e. divided by the number of moves, sqrt: square–root), which explanatory variables had a significant influence (p-values of 0.001 designate $p < 0.001$), and the diagnostics from the analysis of residuals (cp. Statistical methods, 1: qq–plot, 2: TA–plot, 3: residuals versus border, 4: residuals versus time; s: there were steps in the normal plot, o: outliers, uv: unequal variance; diagnostics in parentheses refer to minor deviations. Some test were rerun without outliers (w/o plus number of outliers).

Response variable		explanatory variables			analysis of residuals			
	trans	border	time	inter-action	1	2	3	4
Number (#) of moves	sqrt	ns	0.001	ns	s/o	uv	ok	uv
dito, w/o 11	sqrt	0.001	0.001	0.001	(s)	ok	ok	uv
Median # of visits	c	0.001	ns	ns	(s)	ok	(uv)	ok
IQR of # of visits	sqrt	0.001	ns	ns	(s)	ok	ok	ok
Median # of visits to edge	c	0.001	ns	ns	(s)	ok	ok	ok
IQR of # of visits to edge	sqrt	0.001	ns	ns	(s)	ok	ok	ok
IQR of # of visits to edge	c, sqrt	0.001	ns	ns	(s)/o	ok	ok	ok
dito, w/o 2	c	0.001	ns	ns	(s)	ok	(uv)	ok
# of fields with no visits	c, sqrt	0.001	0.02	ns	(s)/o	ok	ok	(uv)
dito, w/o 1	c, sqrt	0.001	0.04	ns	(s)	ok	ok	ok
Median # of meetings	c	ns	ns	ns	ok	ok	ok	ok
Range of # of meetings	c,	0.01	ns	ns	ok	ok	ok	ok
Median length of meetings	sqrt	ns	0.001	ns	o	ok	ok	uv
dito, w/o 1	sqrt	ns	0.001	ns	ok	ok	ok	uv
IQR of length of meetings	sqrt	ns	0.001	ns	(s)	ok	ok	uv

Figures

Figure 1: Normal–plot, Tukey–Anscombe plot (with a loess smoother fitted) and residuals versus variables of a model. These are typical plots for the evaluations in this study. Shown here are the residuals of the median number of visits to the fields per number of moves modelled by border.

Figure 2: Number of moves, median number of visits per field and inter–quartile range of the number of visits to the fields split by the approaches to model time and border.

Figure 3: Median number of visits to fields on the edge of the lattice, inter–quartile range of the number of visits to fields on the edge of the lattice (uncorrected and corrected) and number of fields with zero visits split by the approaches to model time and border.

Figure 4: Median length of meetings with the four other animats, range (maximum minus minimum) of number of meetings, median length of meetings with one other animat and inter–quartile range of the length of the meetings split by the approaches to model time and border.

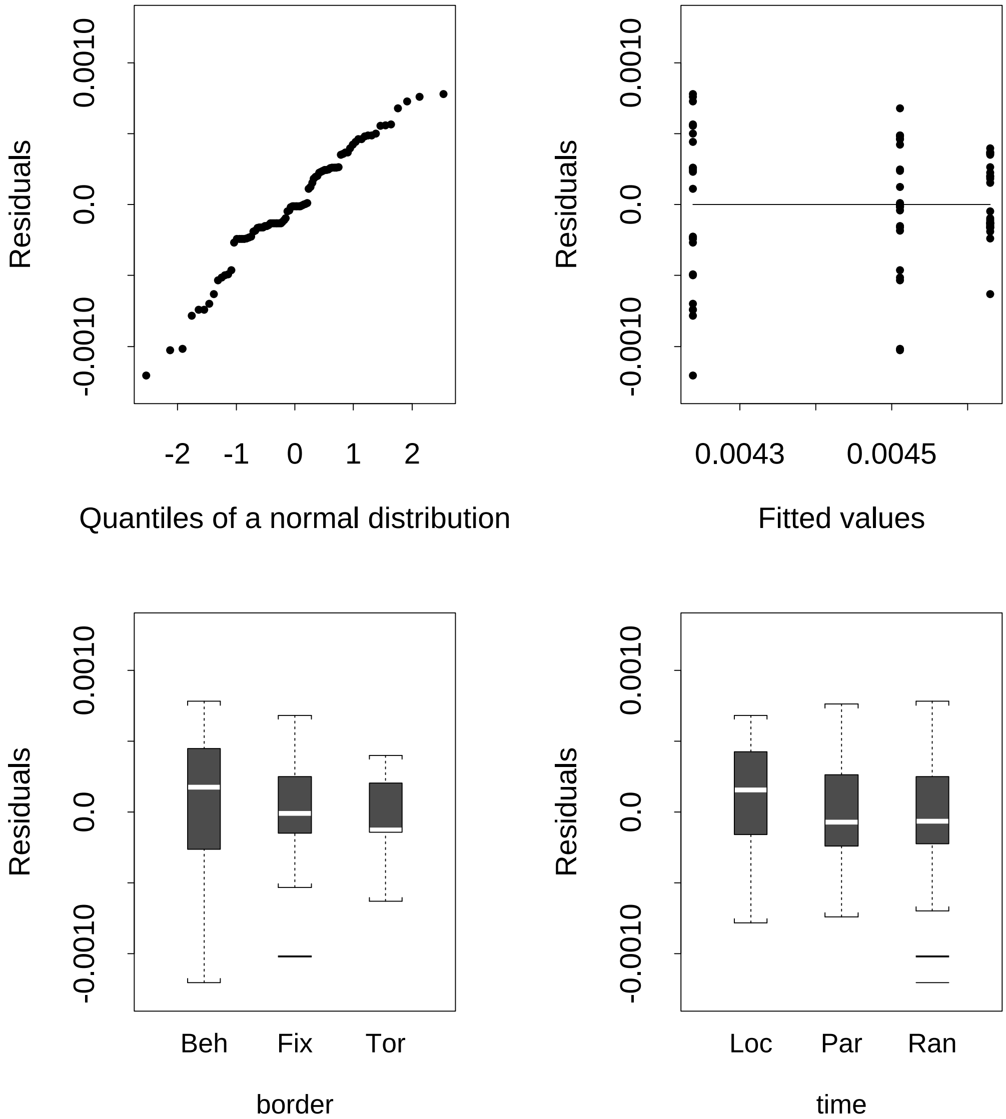

Fig. 1
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Time and home–range borders

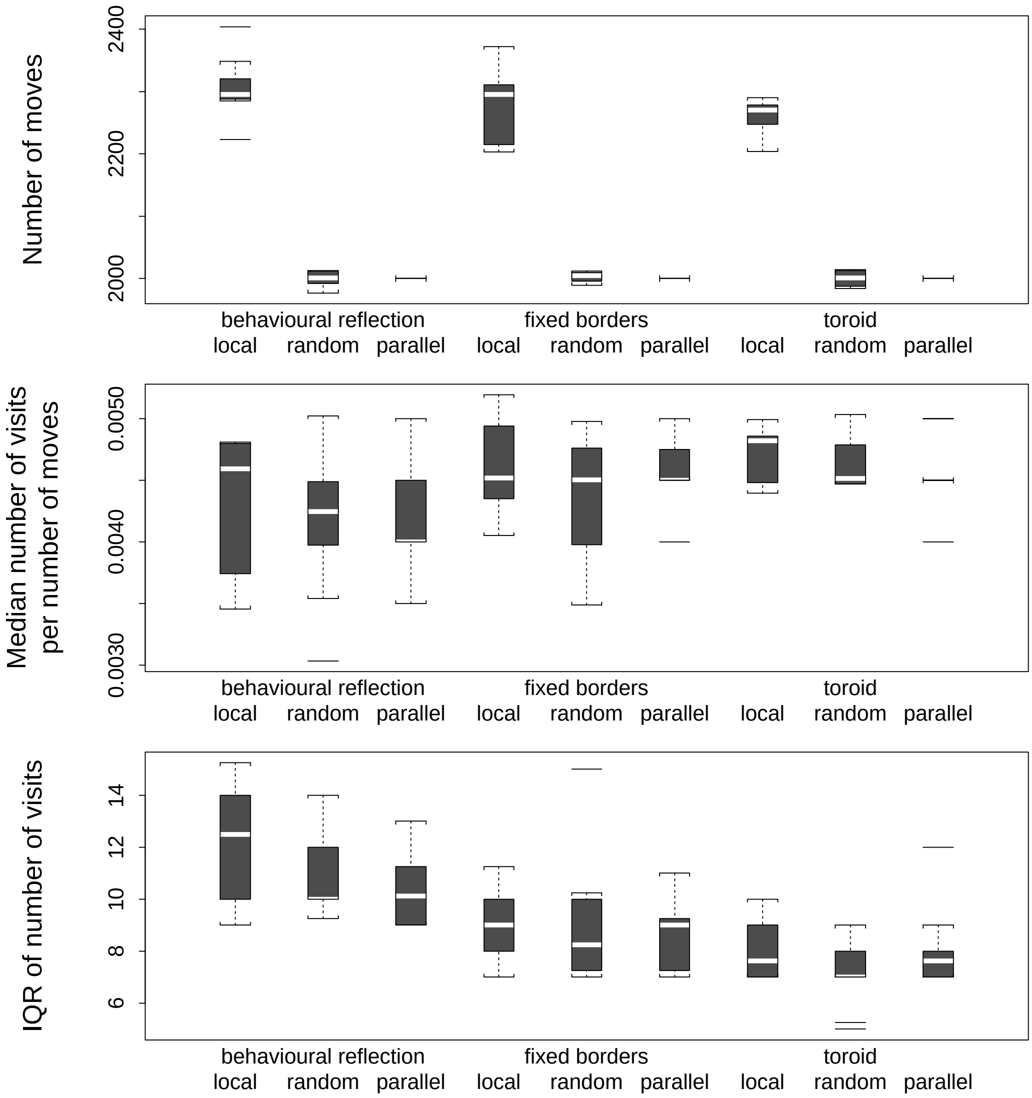


Fig. 2
Lorenz Gygax
Time and home–range borders

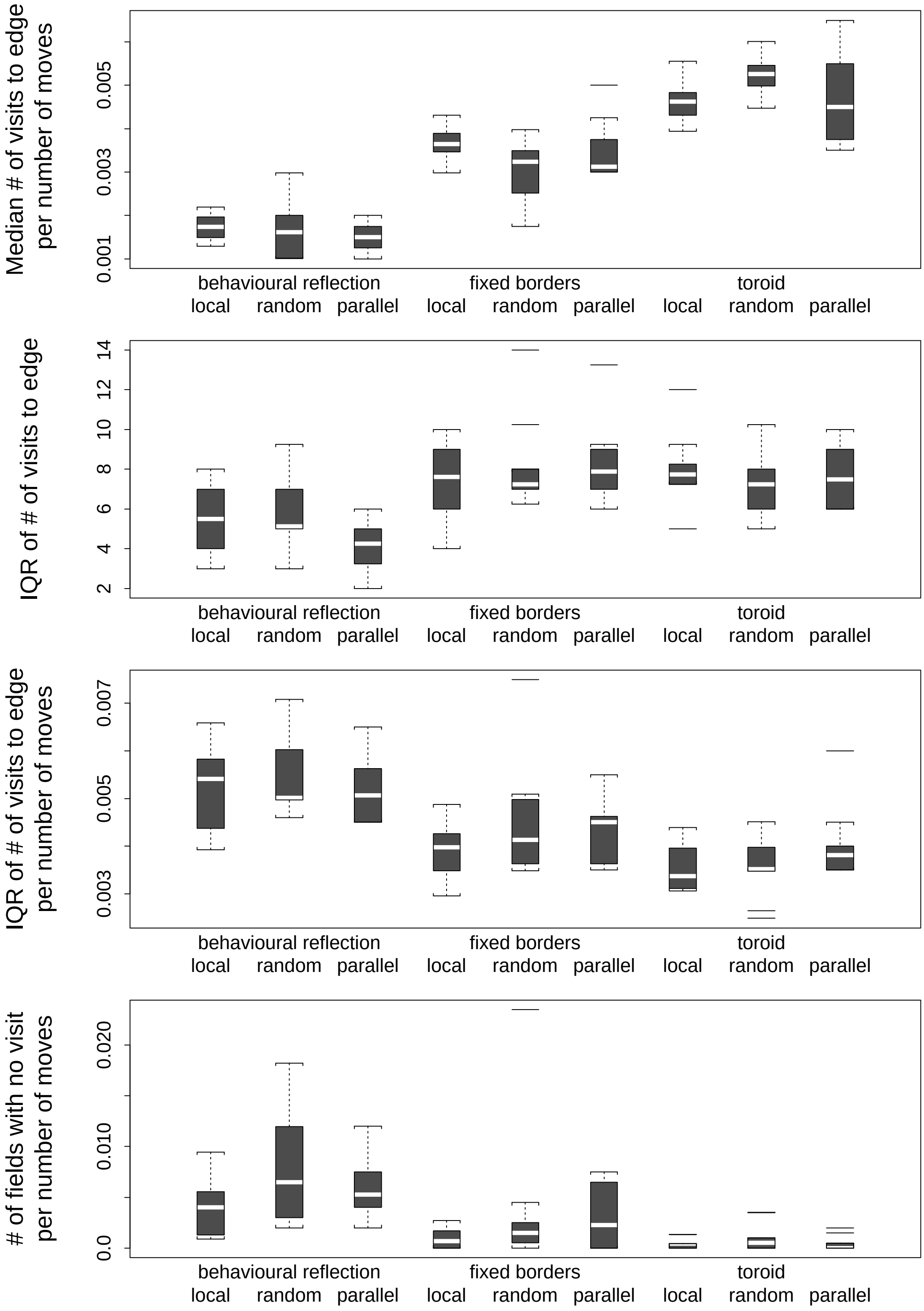
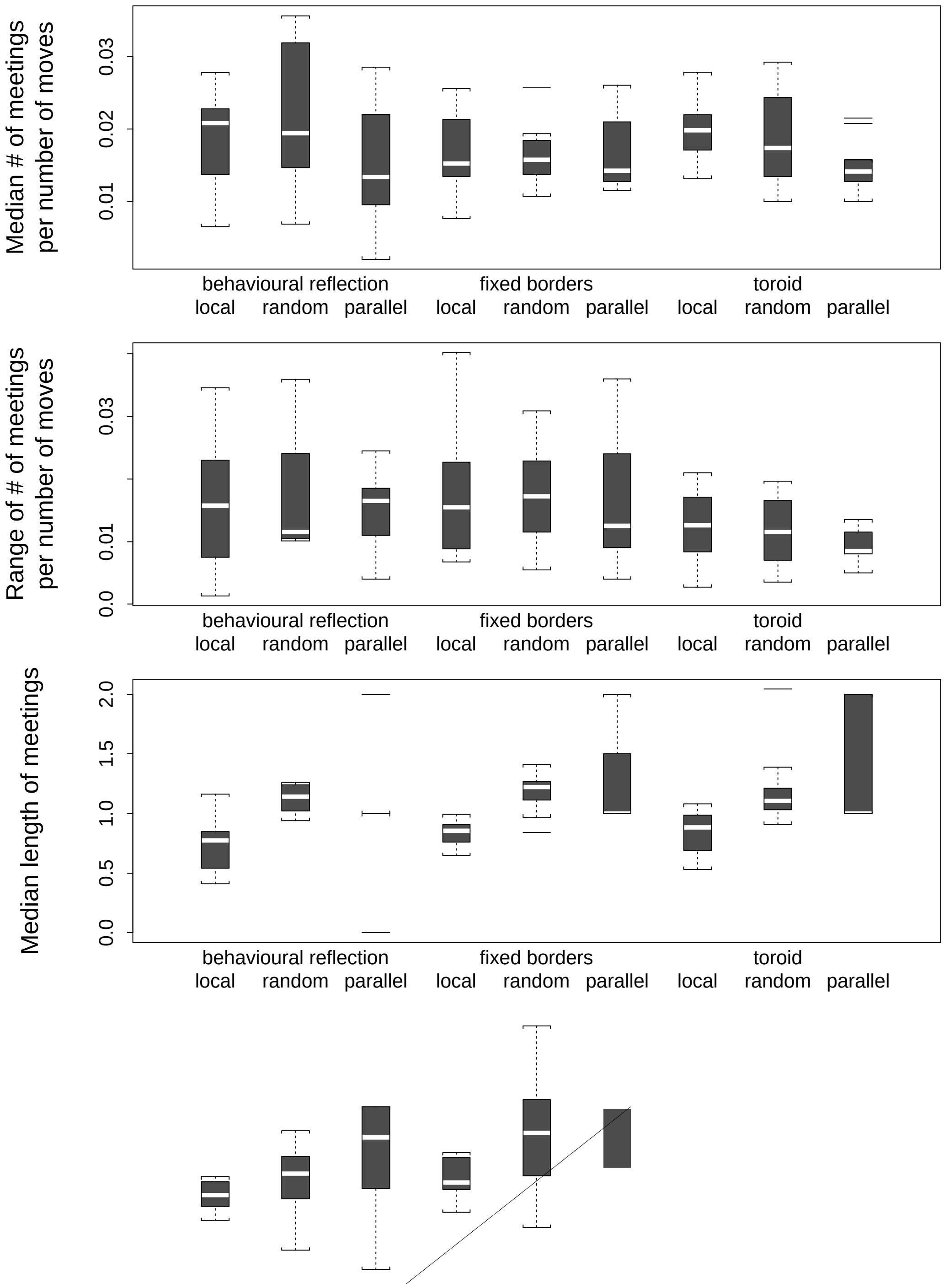


Fig. 3
Lorenz Gygax
Time and home–range borders



Median # of meetings per number of moves
0.01
0.02
0.03
behavioural reflection
fixed borders
toroid
local random parallel local random parallel local random parallel
Range of # of meetings per number of moves
0.0
0.01
0.03
behavioural reflection
fixed borders
toroid
local random parallel local random parallel local random parallel
Median length of meetings
0.0
0.5
1.0
1.5
2.0
behavioural reflection
fixed borders
toroid
local random parallel local random parallel local random parallel