Time-structure analysis in a village community of Columbian Indians

A mathematically simulated system of ultradian oscillators

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Abstract

Studies of daily behaviour patterns in a village community of Columbian indians provided evidence that individual ultradian behaviour cycles can be synchronized by social interaction. In order to understand this mechanism and its significance with respect to the time-structure of daily activities in small hunter-gatherer communities, a mathematical model was developed. The proposed model generates dynamical portraits of locomotor activity and social aggregation similar to those of the observed village community. In addition it gives support to the hypothesis that social synchronization of ultradian behaviour cycles contributes to the ecomnomy of individual and common effort in gathering and related activities. Since ultradian behaviour rhythms can be considered as a biological heredity humans share with other species, it is speculated that the social synchronization of ultradian rhythms had already coordinated the individual activities in early hominids groups according to a common time-frame, long before man had mastered the conceptualization of time.

Key words: hunter-gatherer community, numerical experiments, limit cycle oscillators, social synchronization, space-time portraits, survival mechanism

Humans as a biological species have developed on the socio-cultural level of small hunter-gatherer communities over a period of at least about 1 million years. Recent tribes of so-called primitive races still living at the cultural level of the stone age are thought to represent a model of that ancient state of human evolution. Many anthropologists have therefore addressed their efforts to investigating the distinct forms of social organization, economy and cultural patterns which characterize hunter-gatherer communities all over the world (for a review, see Lee and DeVore, 1972). Hunters and gatherers in different parts of the world live in groups of about 20-40 individuals. They exploit natural resources, but do not keep the collected food in stock. Since machines or related technical equipment are not available, their survival depends crucially on their mutual cooperation and economy of physial effort. This implies a particular organization of their daily life which enables them to synchronize their individual activities and provide a means of optimal coordination, even though they are not familiarized to artificial time measuring. The same is valid for `neolithic` planters which still practice a technically primitive horticulture supplemented occasionally by hunting and gathering.

In technically more advanced communities the cognitive conceptualization of time serves to coordinate individual activities within a common frame. Particularly, the civilized people of modern industrial communities are subjected to artificial schedules all regulated according to clocktime. But, temporal organization of behaviour is also a biological phenomenon which operates over and above the cognitive conceptualization of time. As demonstrated in numerous laboratory as well as field studies, a variety of physiological and behavioural functions in humans, animals and even plants is regulated by several endogenous rhythms. Beside seasonal and circadian rhythms, endogenous cycles with periods of about 1 or a few hours can be found. Since these short-term rhythms have a higher frequency than circadian ones they are called ultradian cycles. There is no doubt, that circadian rhythms with periods of about 24 hours serve to adjust all organisms to the geophysical day-night regimen, since they can be exactly synchronized to the 24-hour period by several, external cues ("Zeitgeber"). But why ultradian cycles? What benefit is there in short-term rhythms which subdivide the 24-hour interval into several periods of a few hours each ? For humans, particularly, ultradian cycles, well documented under laboratory studies, are generally disguised in daily life by modern socioeconomic schedules. For instance, most civilized people are accustomed to fixed meal times even though endogenously regulated appetite, demonstrated by ad libitum feeding as well as by monitoring of gastric contractions in fasting subjects, follows a cycle of about 1 1/2 hours (Friedman and Fisher 1967; Hiatt and Kripke 1975). Similar endogenous cycles are manifested in alternating phases of rest and motor activity and temporal variations in perception and cognitive style (Globus et al., 1973; Lavie, 1976; Klein and Armitage, 1979).

In contrast to civilized people, some illiterate communities still living under natural conditions are neither subjected to external schedules nor familiarized to artificial time measuring by watches or clocks. Hence, endogenous time structures might play a more important part in organizing their daily patterns of behaviour. As a first step of search for ultradian behaviour cycles and time structures in a group of recent hunters and gatherers, the authors studied daily activity patterns in a community of Guahibo-Sicuani, living in the Llanos Orientales of Columbia . Nowadays, Guahibos are slightly ac-

culturated and have developed settlements in small villages, but they still exploit nature by gathering, hunting and fishing. Beside this ancient form of subsistence economy, they traditionally practice a primitive slash and burn horticulture by clearing the forest with fire and planting yucca (for a review, see Reichel-Dolmatoff, 1944).

Methods

General scheme of data collecting

The observed community of about 40 persons was settled in a village, Corocito, 20 kms from Puerto Gaitan at the Rio Meta

The village included five family huts and one common cooking hut situated in an area of about 100 x 100 mts (fig.1 sketch above). Using a pedometer, the distances from one hut to the others were measured in order to draw a map showing the arrangement of huts and the net of pathways inbetween (fig.2. below). The observations undertaken in March 1986 referred to single individuals as well as to subgroups of the community.

Since the rainy season was expected, the adult men worked frequently in lots of the forest they had cleared by fire. In order to determine time series of individual daily activities the observer focused on a single predetermined subject and recorded his/her activities into a note-book over 7-9 hours per day. When the records were categorized and plotted against the time of day, particular scores of behaviour resulted (fig.2). The variations of individual scores are compared and analysed with respect to ultradian periods (Fig.3 .

In order to prove whether temporal variations of individual activities can be synchronized by social interactions the observer   focussed on distinct subjects of a subgroup and   recorded their activities into note-books. Since detailed scores of behaviour could not be determined simultaneously for more than two individuals, group activities had to be defined by other criteria. Within the village the individuals walked frequently from hut to hut in order to communicate or to give mutual support in managing several activities. From one hut to the other they took distinct pathways in order to protect their bare feet from sharp blades of grass. When some individuals left the village, they gathered food in a forest lot or carried water from a well nearby. Since locomotion was their common pattern of activity, it could be chosen as a particular item of behaviour. In order to define a measure of individual locomotion, a grid of arbitrary 14 x 14 square units was projected over the map of the village (fig. 1 below). The area of a square unit, 8 x 8 mts. corresponds to the mean size of the huts. The traces of individuals

observed during consecutive time samples of 5 or 10 minutes were transcribed on to the map. The number of square-units visited during a sample interval could be used as a measure of locomotion. Thus, individual time series of locomotion resulted. In order to define a group locomotion the time series of several subjects observed simultaneously were averaged   Fig. 1

In addition to the individual locomotions of some few subjects, the number of persons assembled at special sites, such as family huts or the common cooking hut, was counted for consecutive sample intervals of 5 minutes. This shorter sample interval was chosen since the number of assembled persons varied more rapidly than the data of individual and group locomotion. Finally, the number of assembled persons was plotted against time of day. Corresponding time series are referred to below as 'social aggregation'.

Time series analysis

Locomotion of a particular subgroup and social aggregation at one of the huts could be observed simultaneously during four days (Fig. 6). The procedure of mathematical analysis can be demonstrated using the group locomotion of three women observed on the 27th March as an example. As a first step, moving averages were calcalated for the time series of group locomotion. Their plots represent a mean level around which the values of locomotion fluctuate (Fig. 5). The autocorrelogram of these fluctuations indicate a periodicity. Finally, a Fourier transformation of the autocorrelogram yields a autospectrum with a clear peak at the frequency of 13 cycles per day, i.e., a period of 111 minutes. Using the same procedure time series of both, group locomotion and social aggregation observed at four days were analysed with respect to ultradian periodicities.

Results

Ultradian variations in the score of individual behaviour

During March the adult men were frequently engaged in planting yucca in several lots of the forest they had cleared by fire some weeks before. Using their machetes, they slashed the bush and underwood and broke up the soil by means of digging sticks in order to set planting stocks. In the case that somebody was not engaged in one of these activities he moved around or managed something. For instance, he grinded his machete or prepared the planting stocks. Subjects which had interrupted their work communicated frequently with others or smoked. Otherwise they sat down in order to rest or eat. Since each person showed one of these types of behaviour, his daily activity could be scored according to seven criteria: digging, planting, use of machete, locomotion, managing, social contact and rest. These states of behaviour were skaled according to their degrees of exertation. Finally, the categorized behaviours were plotted against the time of day using a sample interval of 5 minutes. Since the daily activities of three subject were recorded during several days of observation, nine scores of behaviour resulted (Fig. 2).

In order to emphasize the main pattern of activity, highly frequent variations of the raw data were eliminated by a moving averaging procedure (5-point filter: weights 0.5.1.1.1.0.5). This method of filtering yields smoothed scores of behaviour. Their temporal variations indicate oscillations between states of more or less exerting work and states of rest or social contact. The only exception is the aperiodic score of our subject Alejandro on the 17th March. In order to compare the periods of variations found in the other scores, their smoothed diagrams were arranged according to increasing lengths of their mean peak-to-peak intervals and synchronized with respect to their main morning peak. Additionally, corresponding peaks were connected by crest lines which emphasize a waving structure common to the eight scores of behaviour. Their mean interval of 128 (S.D. = 16.5) minutes indicates ultradian oscillations of about 2 hours.

Group locomotion and social aggregation

The traces of individual movements were transcribed on to the map for consecutive sample intervals. In order to give an impression of resulting patterns, the traces of three woman, Lurde, Solear and Vidalia were plottet for sample intervals of 30 minutes each   . The woman engaged in preparation of food moved frequently between the family hut 5 or 6 and the common cooking hut 1   . Additionally, they moved between the cooking hut and the family hut 4, or left the village in order to get water from a well and gather firewood in the forest. When the number of square units crossed by the individual traces was averaged a measure of group locomotion resulted.

For further mathematical analysis, individual locomotor activities and the group locomotion were plotted using a sample interval of 10 minutes (fig.9). Employing again a moving 5-point filter, the raw data could be smoothed in order to minimize the data noise and emphasize ultradian variations. Additionally, a mean trendline of group locomotion was determined employing a second filter of appropriate width (fig. 4, diagram above). Finally, the autocorrelogram of raw data oscillating around the trend line and the corresponding spectrum of variance were computed 5 . The prominent spectral peak indicates an ultradian periodicity of 13 cycles/day, i.e., a period of 111 minutes. This periodicity in group locomotion of three women seems to be caused by synchronization of their individual locomotor activities.

During four days averaged locomotion of a subgroup and the social aggregation of persons in one of the huts were determined simultaneously. The number of persons assembled in a particular site, for instance, a family hut, was determined each 5 minute interval and included individuals of the observed subgroup as well as other persons occasionally present in the hut. Time series analysis of both, group locomotion and social aggregation, yields common ultradian periodicities in the range of 1.5 - 2 hours or subharmonic periods of 3-4 hours (fig. 3   ). The averaged locomotion of a young women and her two children observed on the 19th March showed a period of about 2.5 hours, whereas the number of persons assembled in the common cooking hut varied with a period of about 2 hours (see autocorrelograms and spectra, fig. 6). However, identical periods were found in group locomotion and social aggregation observed during the other three days. The corresponding raw data of group locomotion and social aggregation vary approximately in counter-phase to each other. This means that, for instance, the members of one family spread out periodically and moved separately in and around the village in order to gather, get water and prepare food or managing something. Afterwards they congregated again in their family hut for rest, social activity and meals (see as a good example the diagrams of 25th and 27th March).

Discussion

Individual scores of behaviour were found to oscillate from states of rest to several activities with periods of about 2 hours (fig.4). This periodicity was obviously not generated by external time-cues, since the Columbian indians were neither familiarized to time measuring by means of watches nor subjected to artificial schedules with inherent periods of the observed range. Phases of rest alternating repeatedly with those of activity might be interpreted in terms of periodic recreation from physical effort. There is, however, an alternative line of interpretation. The observed periodicities correspond to endogenously driven, ultradian cycles found in both, physiological and behavioural functions of subjects tested under laboratory and clinical conditions. Since Aserinsky and Kleitman (1953, 1955) had discovered that the stages of sleep were periodically organized according to an approximately 90-minutes cycle, a variety of systems were found to be modulated by an identical or similar periodicity during both daytime wakefulness and nocturnal sleep. For instance, gastric motility (Hiatt and Kripke, 1975) and ad libitum oral intake (Friedman and Fisher, 1967), urine flow and electrolyte concentration (Lavie and Kripke, 1977) as well as spontaneous locomotor activity and several perceptive performances (Globus et al., 1971; Lavie, 1976) are influenced by endogenous rhythms of about 90-120 minutes. Additionally, periodic variations in the cognitive style can be related to an ultradian rhythm which modulates the functional predominance of one cerebral hemisphere compared with the other (Klein and Armitage, 1979; Meier-Koll, 1989 a, b). Further evidence of ultradian behaviour cycles in humans came from clinical studies. Mentally impaired patients are engaged predominantly in repetitons of meaningless stereotyped movements such as body rocking, hand waving and clapping. Since severe mental impairment implies both loss of cognitive skills and autistic self-isolation from the social environment, the stereotyped behaviour of mentally handicapped can be considered as a appropriate clinical model of free-running ultradian cycles (Meier-Koll and Pohl, 1979).

An integrative view of 90-120 minute ultradian rhythms yields from Kleitman's concept of a Basic Rest-Activity Cycle (BRAC) operating throughout wakefulness and sleep (Kleitman, 1963). However, Kleitman's concept has been challenged by studies demonstrating that the cycle of REM phases is a process triggered by sleep onset (Moses et al. 1977, 1978; Campbell 1987). Consequently, ultradian behaviour cycles of the waking organism and the REM cycle of sleep have to be considered as separated components of a multi-oscillator system. It organizes the periodic sequence of distinct stages during the nocturnal sleep, whereas in waking humans it modulates their psychophysiological functions and scores of behaviour (Broughton, 1975).

The range of periods found in the behaviour scores of the Columbian indians corresponds to those of ultradian rhythms studied under laboratory und clinical condition. Hence it can be concluded that the observed behaviour cycles of individuals were triggered endogenously by ultradian oscillators. Like circadian 'clocks', human ultradian behaviour cycles seem to be variable in their period, at least within the range of about 90-120 minutes. For that reason a short period may be extended and a longer one shortened in order to become synchronized to each other. Several studies in both caged and free-ranging animals provide evidence that ultradian behaviour cycles with similar periods exist in a variety of species and can be phase-locked and synchronized by social interaction.

Short-term cycles of locomotor activity and foraging behaviour are known in laboratory mice and rats, but can be observed more conspicuously in other small mammals, such as shrews and voles (Crowcroft, 1954; Davis, 1933). In these small rodents the short-term activity of locomotion and foraging is basically a cycle of food intake alternating with digestive pauses. The ultradian cycle of about 2 hours appears as a stable periodic pattern phase-locked to the daily period of light and darkness. The cycle is expressed differently during the light and dark phase of 24 hours, usually more prominent in the light. The short-term period is obviously related to a species' metabolic demands, since it increases with body weight (Daan and Slopsema, 1978). However, this finding does not imlpy that the ultradian rhythm is generated by a metabolic process.

Several individuals of the common vole (Micrtotus arvalis) undertake their foraging trips more-or-less synchronously, in cage as well as under field conditions. Therefore the 2 hour cycle can be detected also at the population level. As pointed out by Daan and Slopsema (1978), this may lead to the additional benefit of reduction of predatory risk by safety in numbers: a vole taking its meal at the same time of day as its conspecifics may have a slightly smaller chance of predation than if it chooses a different time.

Ultradian cycles in locomotion and other behaviours are also obvious in free-ranging howler monkeys (Altman, 1959) and in rhesus monkeys (Delgado-Garcia et al., 1976). The mobility and behaviour of rhesus monkeys placed alone or in pairs in a sound-proofed and temperature controlled laboratory cage was found to show ultradian rhythms of 70 minutes during 12 hour daily light periods (Delgado-Garcia et al., 1976). Inspite of this, the mobility was considerably reduced during 12 hour dark periods ultradian cycles of about 120 and 50 minutes were obvious. This suggests that an endogenous ultradian rhythm modulating the monkey's locomotor activity continues throughout day and night, but with different intrinsic periods. Neither random noise nor restriction of food and water change

this cycle considerably. Spontaneous behaviour occurred in regular sequences within each cycle interval. Pairs of monkeys synchronized their individual mobility and behavioural cycles. This was obviously not a simple consequence of dominance and submissiveness. Frequently, the submissive animal had to be judged as the stronger synchronizer, since it initiated movements such as jumping or going to the feeder, and was followed by its partner, who occasionally attacted when its dominant position was challanged. As furthermore demonstrated by Delgado et al.(1978), social synchronization of behavioural cycles in monkeys is not an artifact of captivity, since it can also be observed in animals living in an open field situation.

. In humans, social synchronization of ultradian behaviour cycles were found to operate at the level of families or other small groups (Gast and Meier-Koll, 1986). On this line of evidence, short term periods observed particularly in group locomotion and social aggregation of our village community could result from social synchronization of individual behaviour cycles. In contrast to circadian rhythms which obviously serve to adjust diurnal and nocturnal activities to the geophysical day-night regimen, the adaptive significance of an ultradian time-frame is obscure, since short-term periods of about 2 hours have no counterpart in the environment. However, one may argue that in psychophysiological functions, as well as in behaviour, confusion will be avoided if different and partly contradictory states of behaviour are organized according to several phases of a short-term cycle. Furthermore, the existence of ultradian behaviour cycles in single subjects suggests that social life in a community may be patterned by behaviour cycles of its individuals. Since different individuals carry intrinsically regulated ultradian rhythms modulating their behaviour according to about the same period, their activities can by synchronized by social interactions. From this point of view, the social synchronization of individual ultradian behaviour cycles may be regarded as a mechanism influencing the time structure of daily activities in small communities over and above the cognitive conceptualizations and plannings of their members. In addition, from an evolutionary point of view, social synchronization of ultradian behaviour cycles might contribute to the economy of physical strength and common effort of humans living as hunters and gatherers or primitive horticulturists. This particular aspect will be discussed   :
supposing a computer model for socially coupled ultradian oscillators which yields theoretical portraits of group locomotion and social aggregation.

Premisses from Animal and Human Studies

From these findings it is tempting to deduce some basic assumptions governing loco-motor activities in small communities like the observed community of Guahibo-Indians. We summarize the essential hypotheses of related animal and human studies as follows:

1. Each individual carries an endogenous oscillator which operates throughout day and night.
2. The oscillators of different people are coupled if they contact socially.
3. The oscillator modulates the individual's spontaneous locomotor activity. However, this influence is restricted to the daylight since locomotor activity disappears during nocturnal sleep.
4. During sleep, individual oscillators run independent of each other with slightly different periods.

These premisses are illustrated by a metaphorical sketch of hypothesized oscillators and their modulated influence on locomotor activities of three subjects (fig. 7). During the night, the individuals rest or sleep separately without social contact. Their locomotion habits disappear but endogenous oscillators operate continuously within their brains (left part of fig. 1). When the sun rises, the subjects wake up and walk around. Social contact leads to synchronization of individual oscillators (middle part of fig. 7). When the sun sets (right part of fig. 1), local activities and social contacts fade away. Consequently, ultradian oscillators run again independent of each other with different periods.

In this paper we want to show that the qualitative ideas outlined above are able to describe locomotor patterns similar to those observed in the community of Guahibo-Indians. In particular, we show synchronization as a consequence of coupling (social contact). To this end we construct a mathematical model on the basis of the assumptions 1.-4. above.

Modelling Assumption 1

To turn our first assumption into mathematical language, we note that neuronal mechanisms underlying ultradian cycles are as yet unknown. However, there is a general scheme of mechanisms producing self-sustained oscillations (fig. 8). An assembly of exciting neurons activate a second one containing neurons which inhibit the exciting cells by recurrent synaptic connections. A cycle starts when the level of pooled neuronal activitiy of exciting and consequently also of inhibiting neurons is very low. Self-activation within

the assembly of exciting cells enhances their neuronal activity rapidly since inhibition is still very weak. With their increasing activity, however, the exciting cells amplify their self-inhibition via the assembly of inhibitory neurons. Therefore, the pooled activity of exciting cells decreases again to a very low level and the inhibiting neurons lose their activator. Then, a new cycle can commence. A similar mechanism seems to work in neuronal structures of the brain stem. Reciprocal and rhythmic patterns of discharges specific for the proposed mechanism where found in two neuronal groups of the pontine and mesencephalic brain (Hobson et al., 1975). They are related to the ultradian periods of the sleep cycle, particularly to the periodically occurring REM phases (McCarley and Hobson, 1975).

Oscillating systems of this kind can be described in mathematical form. Let $x(t), y(t)$ denote the pooled activities of exciting and inhibiting neuronal assemblies at time t, respectively. Then, an oscillator system has the general form

$$\dot{x} = F(x, y), \quad \dot{y} = G(x, y). \tag{1}$$

We assume that (1) allows for a stable limit cycle describing self sustained oscillations of the neuronal activities $x(t)$ and $y(t)$. If such a system is disturbed by external forces it stabilizes itself and returns to its intrinsic oscillation. A limit cycle model was already proposed by McCarley and Massaquoi (1986) in order to simulate the ultradian REM sleep cycle. In contrast to this REM sleep oscillator, basic neuronal mechanisms involved in the generation of self-sustaining locomotor cycles are as yet unknown. Consequently, there is only qualitative knowledge of the construction of the right-hand side functions $F(x, y), G(x, y)$ in (1). However, for our purposes, a phenomenological model is good enough. Note that we only want to make sure that an oscillator system in principle is able to produce particular patterns. A well-known mechanism is as follows

$$\dot{x}_i = T_i[y_i - M - (x_i - M)(q_i - R_i)] =: F_i(x_i, y_i)$$

$$\dot{y}_i = -T_i[x_i - M + (y_i - M)(q_i - R_i)] =: G_i(x_i, y_i) \tag{2}$$

$$q_i = (x_i - M)^2 + (y_i - M)^2.$$

The subscript i indicates that (2) is the oscillator of the i-th individual. It is well known that, for any fixed i, the limit cycle of (2) is a circle of radius R_i about the midpoint (M, M) in the plane. We can always choose M, R_i in such a way that the complete limit cycle is in the positive quadrant of the plane. It is a globally attractive circle so that any evolution (2) initiated anywhere in the plane is being attracted by this circle. The parameter I measures the period of the limit cycle. Radius and period may differ for different individuals. Hence, the dependence of both parameters on the index i. The observations in the village community have shown that, in single individuals, the period T_i increases with the amplitude R_i. Particularly, infants and children have shorter ultradian periods and smaller action range than grown-ups. For a simple dependence of this sort we put

$$R_i = aT_i, \quad a = factor\ of\ proportionality \tag{3}$$

Modelling Assumption 2

So far, (2) describes free running cycles generating oscillations with particular ultradian periods T_i and amplitudes R_i. In order to simulate the influence of social contact, any two oscillators are connected to each other. A particularly simple form of coupling is described as follows

$$\dot{x}_i = F_i(x_i, y_i), \quad \dot{y}_i = G_i(x_i, y_i) + h(t)\epsilon_1 \sum_{\substack{j=1 \\ j \neq i}}^{N} y_j. \tag{4}$$

$$h(t) = \begin{cases} 0 & during\ the\ night,\ 8p.m.-4a.m. \\ 1 & during\ the\ day,\ 4a.m.-8p.m. \end{cases} \tag{5}$$

Note that the coupling of the oscillators in (1) is linear and involves only the y-components. We want these components to represent the oscillations which are observed in the field studies.

Synchronization in Simulation

In a first run of our model, we want to demonstrate that mutual interaction may lead to sychronization. We take $N = 3$ individuals and initiate their oscillations at the same point in the plane at 12 p.m. (fig. 3a). They run independent of each other ($\epsilon_1 = 0$) with slightly different periods. At 4 a.m. social coupling is switched on ($\epsilon_1 > 0$). Figure 3a shows that, indeed, oscillations begin to synchronize. When social coupling is switched off ($\epsilon_1 = 0$) at 8 p.m. we observe desynchronization of the oscillations and quite different phases.

Modelling Assumptions 3 and 4

So far, (1), (5) model individuals which contact each other during daytime. Furthermore, we have observed that the 'contact' leads to a sort of cooperation (synchronization of the oscillators). In this section we draw our attention to the idea that the person's oscillator organizes its locomotion. To this end, we describe the position at time t of the i-th individual in the plane by a two-dimensional vector $r_i(t) = (u_i(t), v_i(t))$, $i = 1, \ldots, N$. Locomotion is then described by the derivative $\dot{r}_i(t) = (\dot{u}_i(t), \dot{v}_i(t))$, $i = 1, \ldots, N$ of this vector with respect to time. We suggest three contributions to locomotion:

$$\dot{r}_i = -\epsilon_2 w_i - \epsilon_3(r_i - r_0) + y_i h(t)\frac{w_i}{\|w_i\|_2}$$

$$w_i = w_i(t) = \sum_{j=1}^{N}(r_i(t) - r_j(t)). \tag{6}$$

definition of the Euchlidian norm for $\eta = (\eta_1, \eta_2) : \|\eta\|_2^2 = \eta_1^2 + x_2^2.$

Here are some explanations in order: The last term on the right-hand side of the first equation in (6) describes how the y-component of the individual oscillator keeps locomotion going. This term is zero at night (see the definition of the function $h(t)$ in (5)) and the vector points to the direction of the vector $w_i(t)$ which is defined in the second line of (6). This vector contains the influence of the position of the j-th individual on the locomotion of the i-th person. The other two contributions on the right-hand side of the first line in (6) are of stabilizing nature: The vector $r_0 = (u_0, v_0)$ is independent of time and points to the position of a village to which all individuals belong and where they are supposed to gather overnight. Indeed. the second term on the right-hand side of the first equation in (6) pulls the group of individuals back to the center of the village if there is no locomotion activity directed opposite to the gradient of social attracting forces. The middle term of the dynamic equation in (6) describes that individuals of different positions attract each other with a strength proportional to their distances. This attracting force. for instance. is very conspicuous when infants or small children try to minimize the distance to their mothers or another related person. They behave as if they would be connected to their mothers by invisible strings. Consequently, in order to represent these social attracting forces. our model should describe the individuals as connected by a net of 'elastic strings'.

ϵ_2. ϵ_3 in (6) are constants of proportionality. If $\epsilon_3 = 0$, the system describes movements of a nomadic group not bound to a permanent basic camp or a village but stabilizing exclusively by social coupling.

Group Locomotion in Simulation

We have simulated the interaction of 15 people in the plane and we could produce the relations of both group locomotion and social aggregation developing during a 'one-day run' of the program. Representing each individual by a coloured point which moves over a TV screen according to the dynamic of the model, a complex pattern of movements can be visualized (fig. 9a). However. since dynamics in two dimensions can hardly be demonstrated by diagrams including the axes of time, a one-dimensional version of the model was considered. This means that individuals have to walk exclusively within a small strip which includes the center of the village (fig. 9b). Consequently, all the positions have only one dimension so that they are represented by a real function $u_i(t)$ depending on time t. The movements of individuals can then be plotted in a space-time diagram as sketched in fig. 4c.

Next. we are going to describe some experiments with the one-dimensional model. We begin with a group of three selected individuals each represented by one of the oscillators shown in fig. 10a. We start the program and follow their position vector which now consists of one component $u_i(t)$ only. Since we have three people, i obtains the numbers 1, 2, 3. The origin of the space-time diagram (fig. 10b) corresponds to the center of the village from which the individuals start and to which they return. During the simulated 'one-day run'. the three individuals begin to move at 4 p.m. through their one-dimensional space. Their positions change periodically around the midpoint representing the center of the

village. The space-time portraits are highly synchronized by 'socially' attracting forces. When locomotor activity disappears after 8 p.m.. the assembly of individuals is attracted to the center. This experiment shows that synchronization of the individuals' oscillators can lead to synchronization of their position vectors.

The space-time portraits of three individuals shown in fig. 3 serve to give a first impression of the simulated dynamics. In order to model a group of realistic size. we took 15 people and simulated their behaviour. The limit cycle oscillations and the movements of this group were determined solving 15 pairs of differential equations (2) and 15 equations of motion (6). A series of experiments was performed from which we show only one in fig. 5. All others have produced similar diagrams. In particular. in all numerical experiments, the assembly of 15 individuals split into subgroups each of which is stabilized by social coupling. Fig. 14 shows two subgroups of individuals staying together the whole day.

Next. we concentrate on the aggregation of the individuals at a particular site, for example. the central area of the village. We count all events where individual space-time traces cross a horizontal range corresponding to the area. A number of individuals found simultaneously within the central area of the village is indicated by the black diagram of fig. 6. During the night. all 15 individuls are assembled in the village. During daytime, however. subjects aggregate periodically there. This is shown by the lower part of fig. 6. On the other hand. the (one-dimensional) position function $u_i(t)$ gives a measure for the locomotion of the i-th individual since it corresponds to the distance covered at a given time t. As a measure of group locomotion. we have averaged the distances covered by all 15 individuals resulting in the curve given in the upper part of fig. 11. In agreement with the observed group locomotion in social aggregation described in the field study, the theoretical model shows periodic variation for group locomotion and for aggregation in counter-phase provided that appropriate values for the parameters e_1, e_2, e_3 are chosen. fig. 12 corresponds to $e_1 = 0.1. e_2 = e_3 = 2$.

Period Distribution and Locomotion in Simulation

Next. we want to find out how our model society behaves under various distributions of the periods of the individual oscillators. As one possibility, the periods of all limit cycles have the same value. for example. 100 minutes. In reality, however, periods of different individuals will differ more or less. Therefore, versions of the model were run with several distributions of periods. There are two extreme cases: All periods are the same or the periods differ widely from each other. If all individuals have the same intrinsic period (100 minutes. for example). their space-time traces couple to a small boundle as sketched in fig. 13 a. In reality. this corresponds to a group where the individual movements are highly synchronized. At least with respect to gathering, this is a quite unsuitable pattern of behaviour. Each individual of a gathering group would search for food or materials at the same site. Therefore. the pattern of high synchronized movement does not allow for a variety in land-using and exploitation of nature. In contrast, a population characterized by a broad distribution of periods ranging from 30 to 170 minutes, for instance, can hardly synchronize their individual activities if a constant strength of social coupling is assumed.

Corresponding space-time traces will therefore show the great diversity as sketched in fig. 13c. With respect to gathering, this diversity grants a variety in exploitation of nature but a common frame of activities would fade out. Since the individuals lose their contact for longer periods of time, they cannot cooperate and support each other. Since hunter and gatherer communities need both, variety of individual exploitation of nature and coordination of activities, optimal conditions are to be expected in populations which are able to balance these claims (fig.13b). This line of reasoning calls for a special distribution of individual periods for which this optimal condition is realized. We have searched for such optimal conditions in our artificial population given by our model.

To this end we need a measure for synchrony and for diversity of individual space-time traces. The average of cross-correlations over all pairs of space-time traces

$$S := \frac{1}{N} \sum_{i=1}^{N} \sum_{\substack{j=1 \\ j \neq i}}^{N} \int_{a}^{b} u_i(t) u_j(t) dt \tag{7}$$

can be used as a measure for synchrony. Similarly, the term

$$D := \frac{1}{N} \sum_{i=1}^{N} \sum_{j=1}^{N} \int_{a}^{b} (u_i(t) - u_j(t))^2 dt \tag{8}$$

measures diversity of space-time traces. The interval $[a, b]$ appearing in (7), (8) describes the time interval of the day in which locomotion occcurs, particularly $a = 4$ a.m. and $b = 8$ p.m. as in the second line of (5). Both terms in (7) and (8) are written down for the one-dimensional space. The value for S decreases if we move from fig.13a to fig.13c. In contrast, diversity D increases at the same time. Therefore, the product $F = S \cdot D$ is a reasonable measure for the balance of synchrony and diversity. An optimum is reached if F obtains a maximum.

Fixing all other parameters in the model, we consider S, D as functions of the periods. In particular, we put $\epsilon_1 = 0.1$, $\epsilon_2 = e_3 = 2$ as above. Also, our model population consists of $N = 15$ individuals. The distribution of the 15 periods we use are described by two parameters: The central period τ_c and the maximal deviation q of all 15 periods from the central period. This is constructed as follows (compare the middle picture in fig.14): On the lower vertical axis we note the central period τ_c. The other horizontal line shows the maximal interval $[40, 170]$ in which we want the periods to distribute. In this interval we choose 15 periods and join them with a straight line to the central period. This constructs a sector which contracts at the central period on the lower horizontal line. Fig. 8 only shows the boundaries of such triangles. The parameter q ranges on the vertical line from zero (lower horizontal line) to 1 (upper horizontal line) and fixes the periods on the horizontal line at level q within the particular triangle. We see that, in this way the distribution of the periods increases with increasing parameter q. Thus, S, D in (7) and (8) are functions of τ_c, q. Since the assembly of 15 space-time portraits are split into subgoups, the function $S(\tau_c, q)$ is calculated under variation of period distribution separately for the two subgroups of space-time traces shown in fig.11. The numerical experiment begins with one of the extreme situations (A) where all individuals have one and the same intrinsic period (lower horizontal line of the middle picture in Fig.14). Then, the range of

periods was consecutively widened as described above to the other extreme on the upper horizontal line in the middle picture of fig. *14*. The diagrams for $S(q, \tau_c)$ given in fig. *14* for four values of τ_c show a maximum plateau for q -values between 0.4 and 0.7 for both groups (bold curves in all diagrams of fig. 8). Any diagram in fig. 8 corresponds to a fixed value of τ_c so that F is a real valued function on the real parameter q only. As shown in fig. 8, we have used $\tau_c = 10, 50, 67, 100, 150, 200, 250$ minutes. Diagrams for distribution with central periods $\tau_c < 100$ minutes are shown on the left-hand side and for distributions with central periods $\tau_c > 100$ minutes on the right-hand side of fig. *14*. In any diagram, the bold curve corresponds to $\tau_c = 100$ and all the other curves belong to further central periods as shown in fig. 8 by the various markers. A glance at the diagrams reveals that distributions around a particular central period (100 minute in our simulation) realize optimal conditions in the sense discussed above. Hence, it seems that optimal conditons are correlated with particular deviations in periods within a community.

Closing Remarks

It can be speculated that this balance provides an advantage not only for daily activities, but on the long run for survival compared with populations equipped with otherwise distributed periods of ultradian locomotor cycles. Since ultradian behaviour cycles have to be considered as a biological heredity humans share with other species, it can be speculated that synchronization of individual ultradian rhythms has already served to coordinate daily activities in small communities of early hominids long befor man has mastered the conceptualization of time. Homo erectus and, particularly, early homo sapiens developed on the socio-economic level of hunter and gatherer cummunities. Ultradian behaviour cycles which were socially coupled in a multi-oscillatory system could have generated a common ultradian time-frame of individual activities of such groups. Like synchrony of foraging or exploratory behaviour in social-living animals, an ultradian time-frame may provide greater security for the individual and may optimize the economy of common effort. Therefore, it might be speculated that social synchronization of individual ultradian behaviour cycles has served as an innate survival strategy for early hominid groups.

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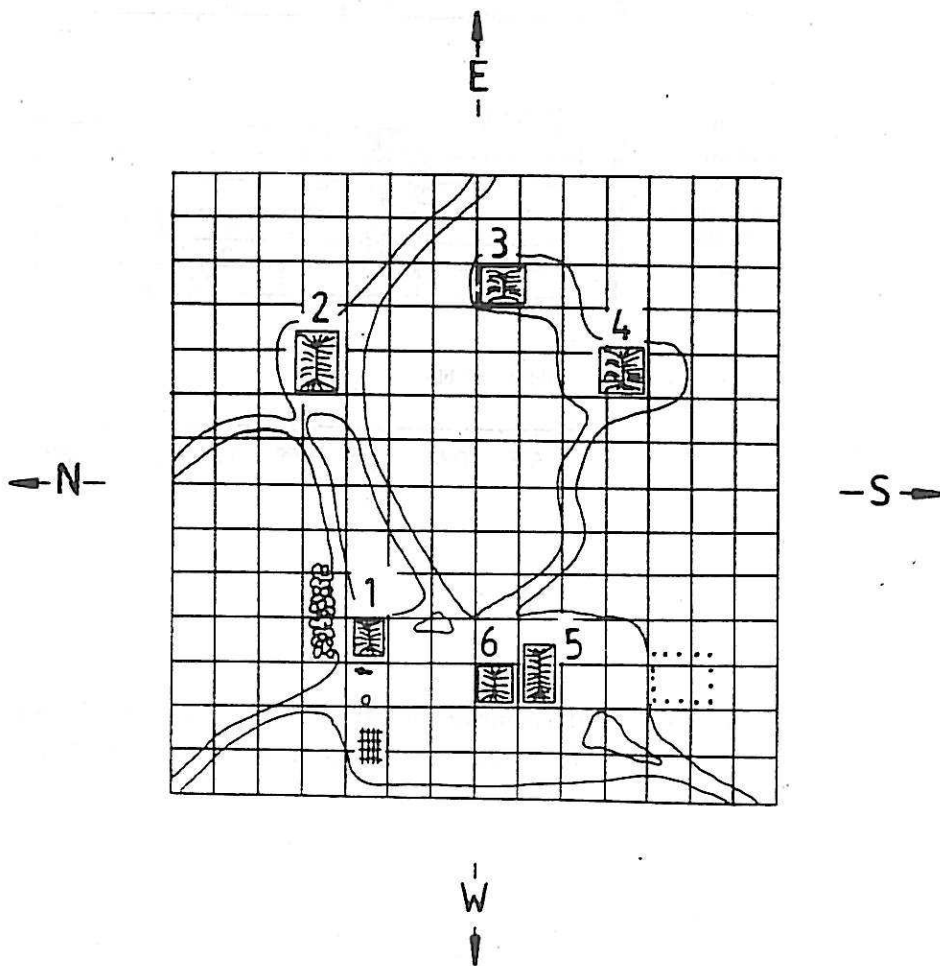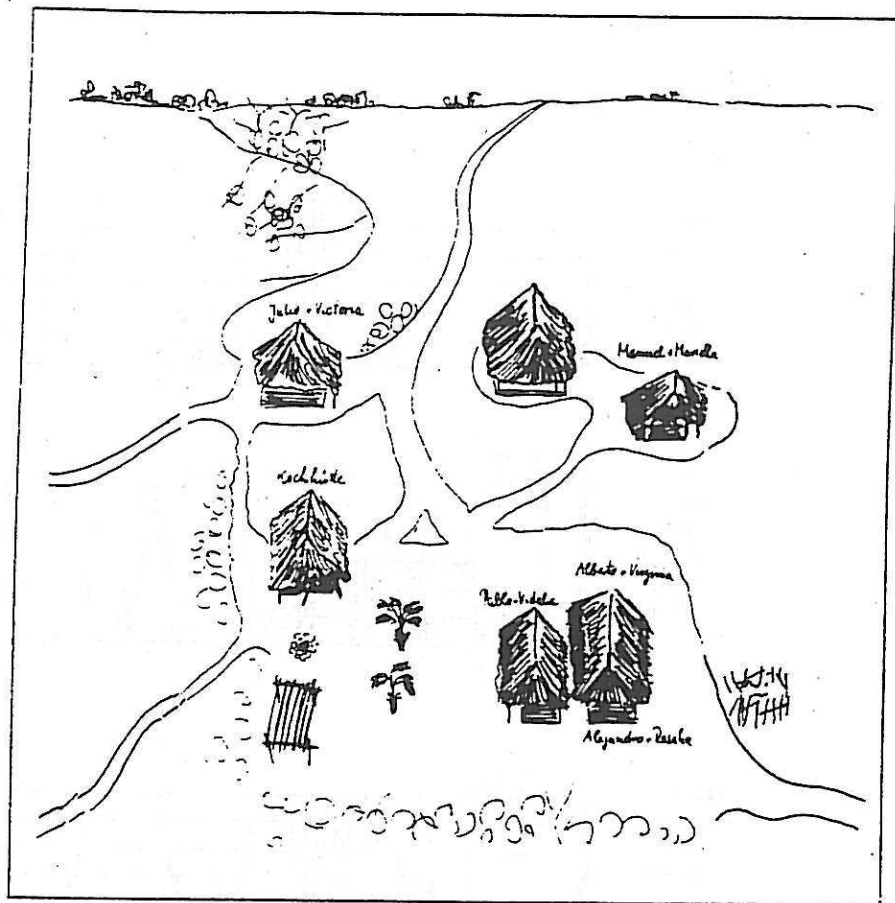
Fig.1 Sketch of the Guahibo village and its map (1 cooking hut. 2-6 huts of families)

scores of behavior

digging
planting
machete
locomotion
managing
social contact
rest

11/3/86

digging
planting
machete
locomotion
managing
social contact
rest

13/3/86

digging
planting
machete
locomotion
managing
social contact
rest

15/3/86

digging
planting
machete
locomotion
managing
social contact
rest

18/3/86

subject   Pablo

6^{00} 8^{00} 10^{00} 12^{00} 14^{00} 16^{00} 18^{00}
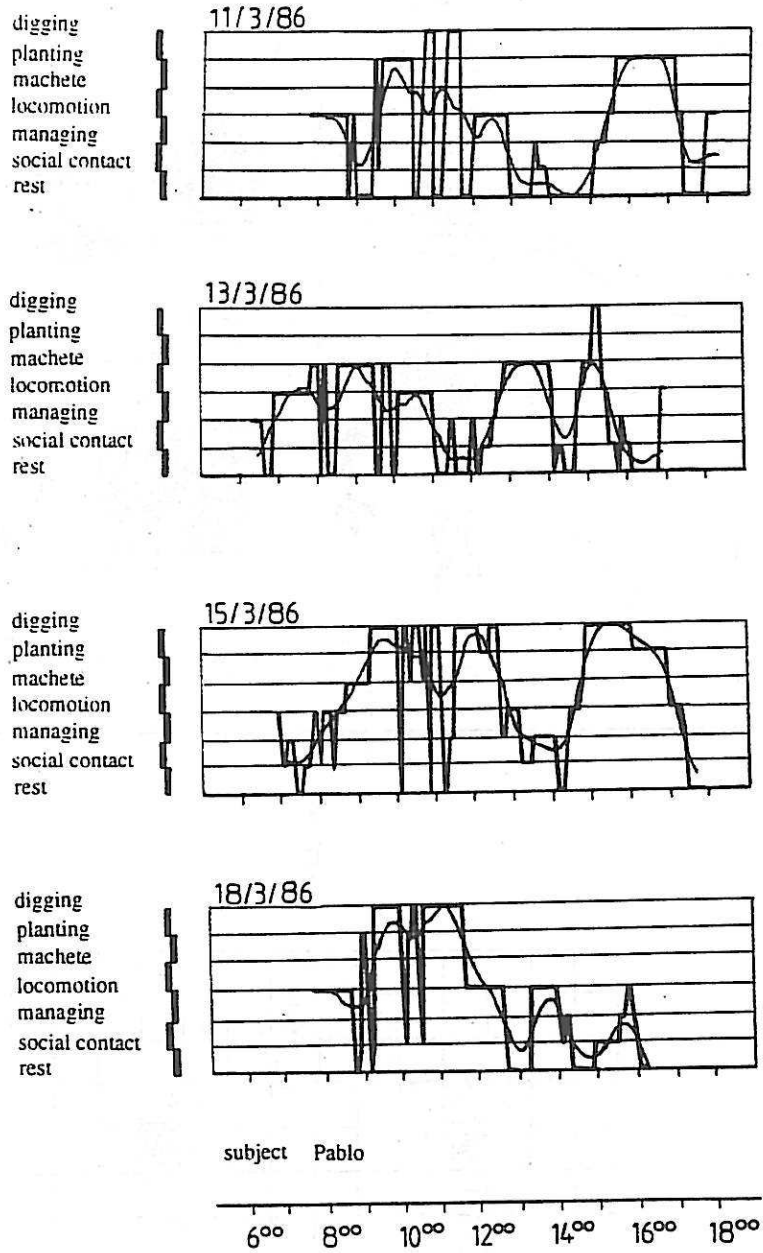
Fig.2 Individual time series of scored behaviour observed in three men during several days.
Raw and smoothed data. Note oscillations between states of rest and several activities.

scores of behavior

digging
planting
machete
locomotion
managing
social contact
rest

17/3/86

digging
planting
machete
locomotion
managing
social contact
rest

18/3/86

digging
planting
machete
locomotion
managing
social contact
rest
sleep

20/3/86
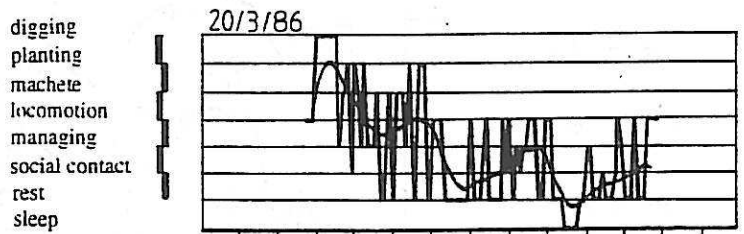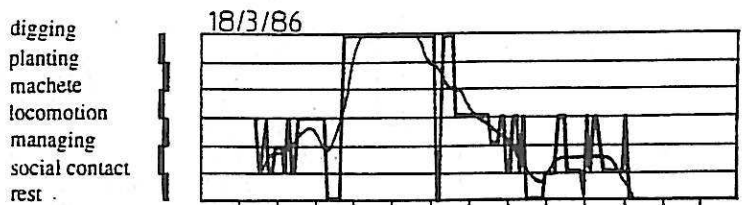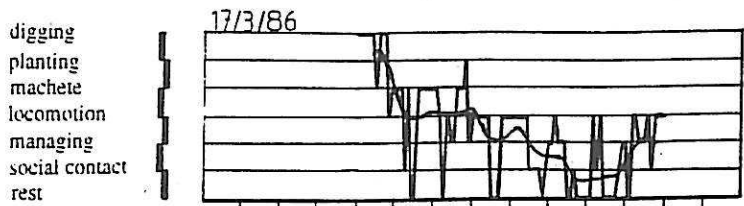
subject   Alejandro

6⁰⁰   8⁰⁰   10⁰⁰   12⁰⁰   14⁰⁰   16⁰⁰   18⁰⁰

scores of behavior

digging
planting
machete
locomotion
managing
social contact
rest

17/3/86

digging
planting
machete
locomotion
managing
social contact
rest

18/3/86
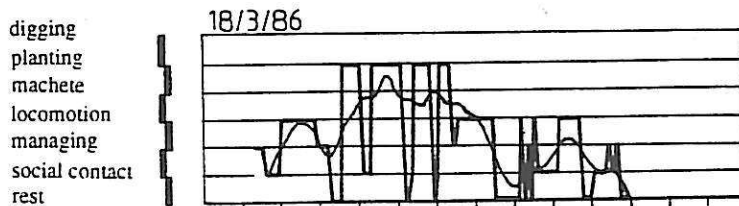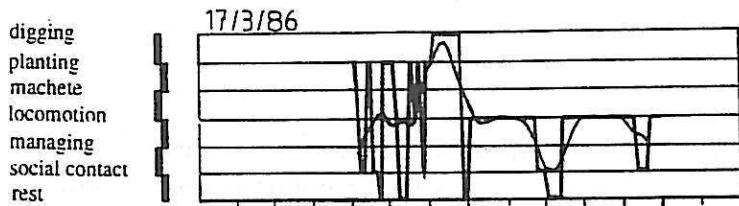
subject   Alberto

6⁰⁰   8⁰⁰   10⁰⁰   12⁰⁰   14⁰⁰   16⁰⁰   18⁰⁰
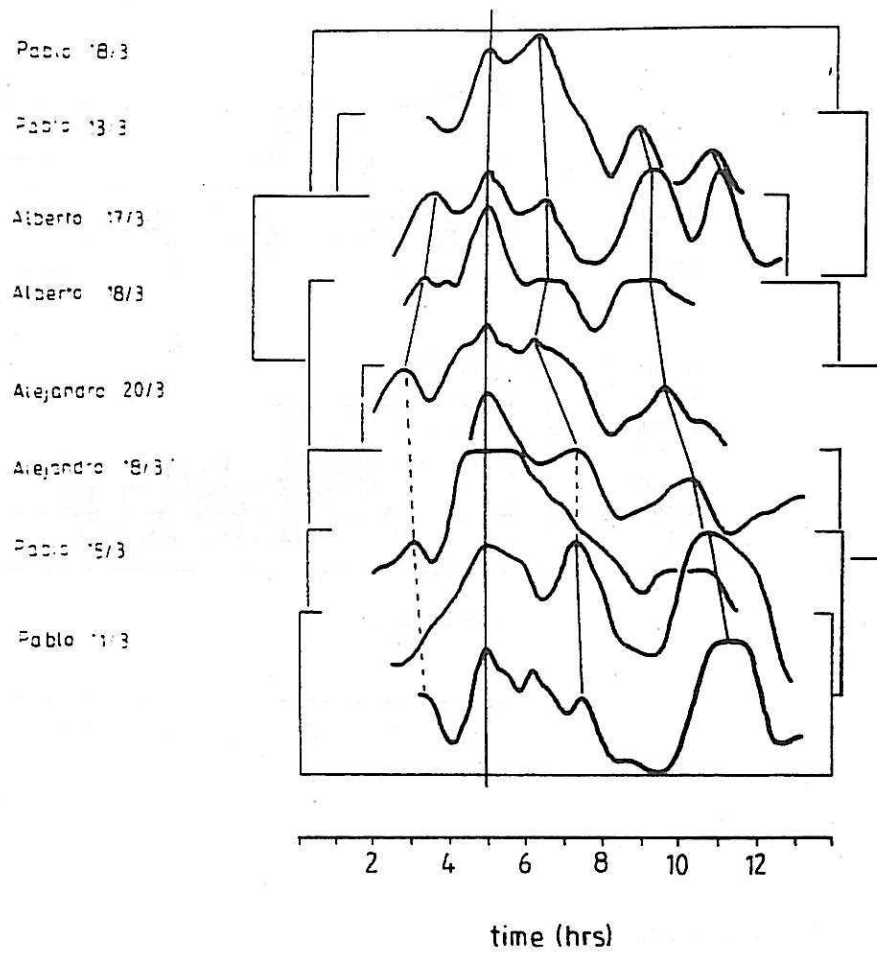
Fig.3 Periodic time-structure of the behaviour scores of three men. Eight of the time series of smoothed data shown in fig.3 were arranged according to their mean peak-to-peak intervals and synchronized with respect to one of their first peaks.

Individual Locomotion
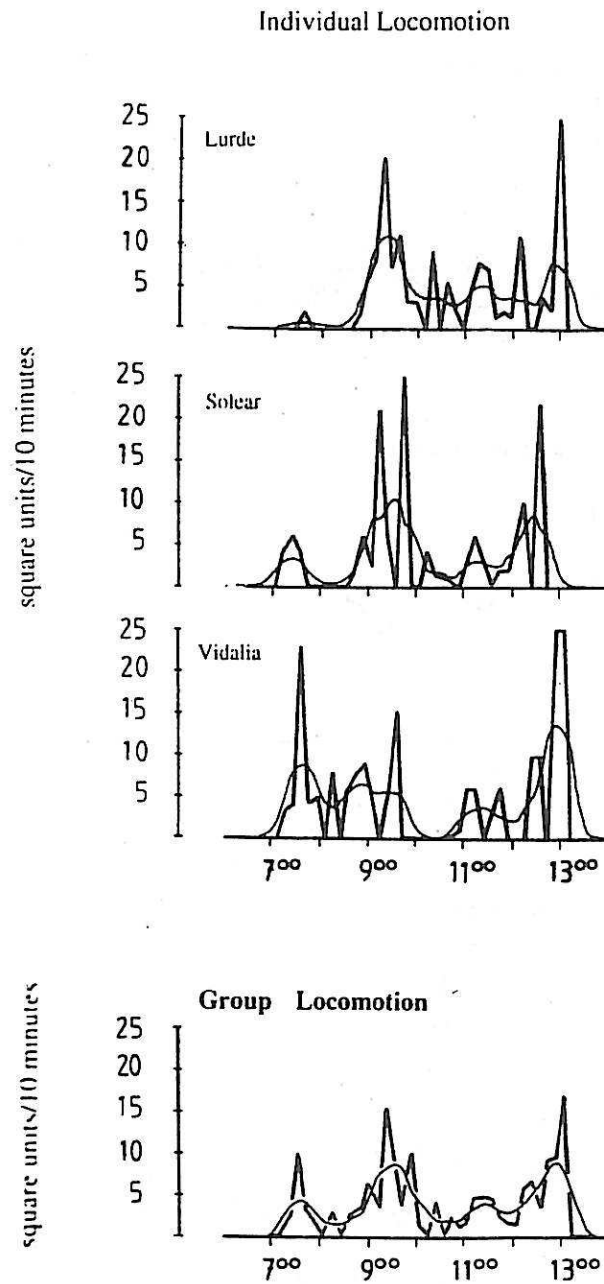
Fig. 1 Above: Time series of individual locomotor activities of Lurde, Solear and Vidalia (number of square units crossed during consecutive samples of 10 minutes). Below: group locomotion averaged from individual locomotor activities. Thick diagrams = raw data, thin diagrams = smoothed data.

Group Locomotion   Lurde   Solear   Vidalia

Autocorrelogram

Time Lag (hrs)

Spectrum of Variance

Frequency (cycles/day) and Periods (hrs)
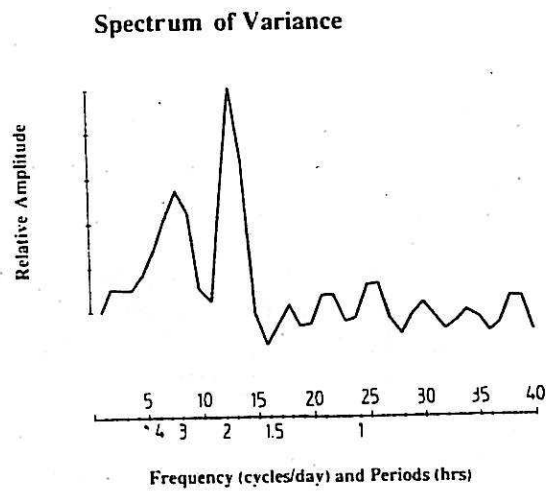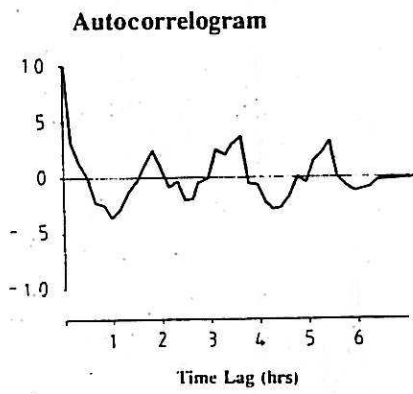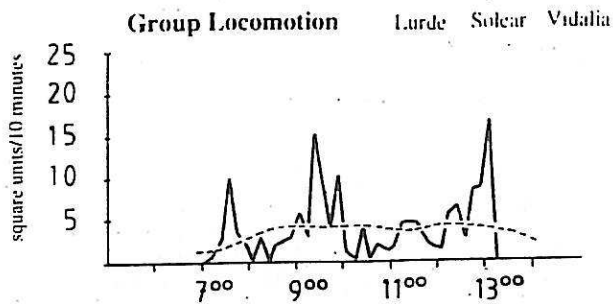
Fig. 5 Upper diagram: group locomotion of Lurde. Solear and Vidalia (dotted curve = trend line eliminating ultradian variations). Diagrams below: autocorrelogram and spectrum of the (raw data) variations around the trend line.
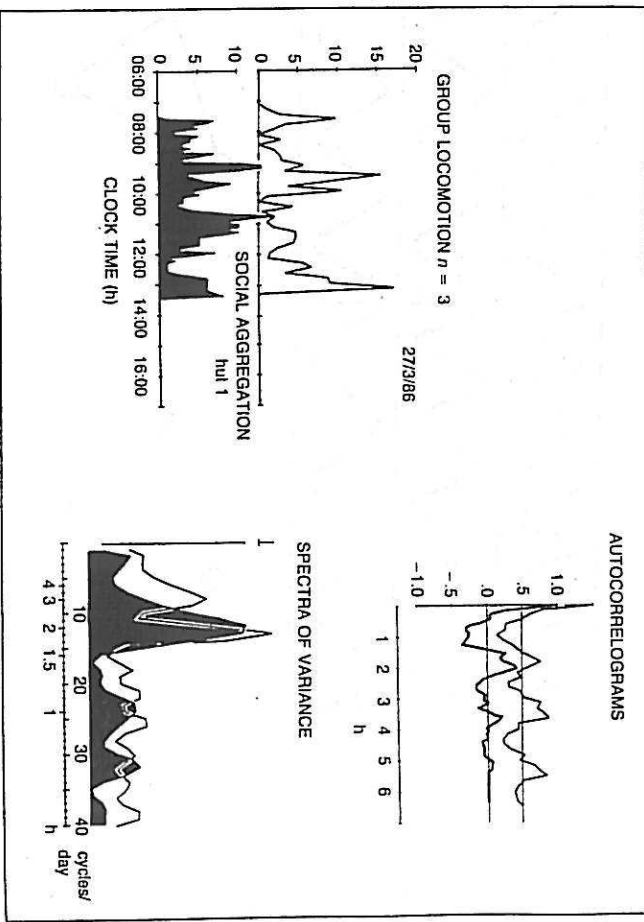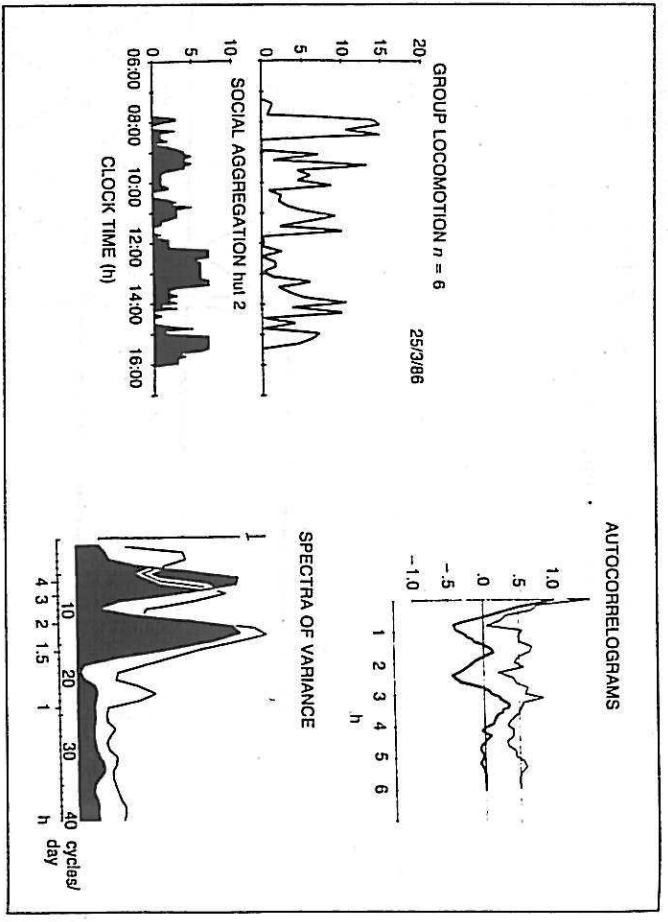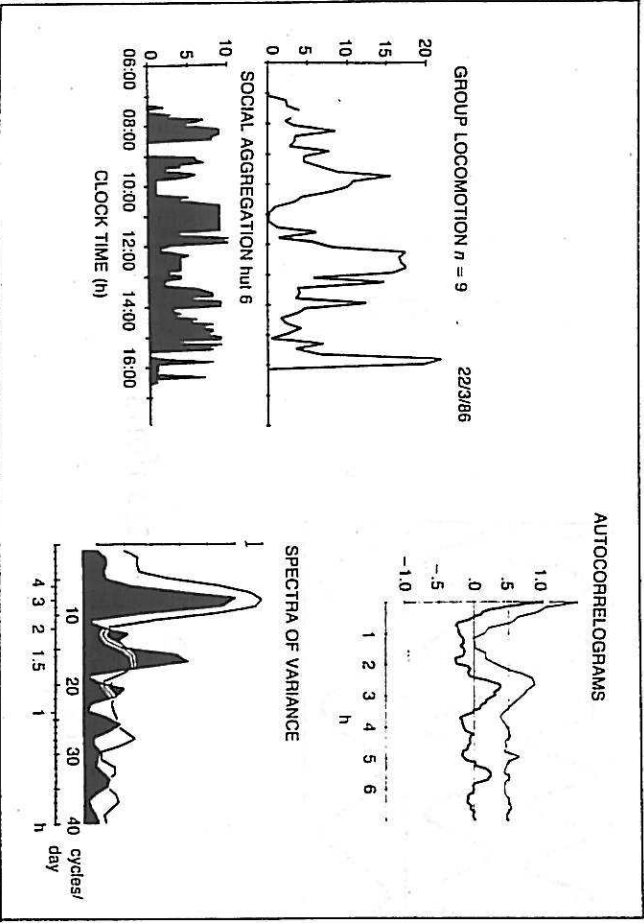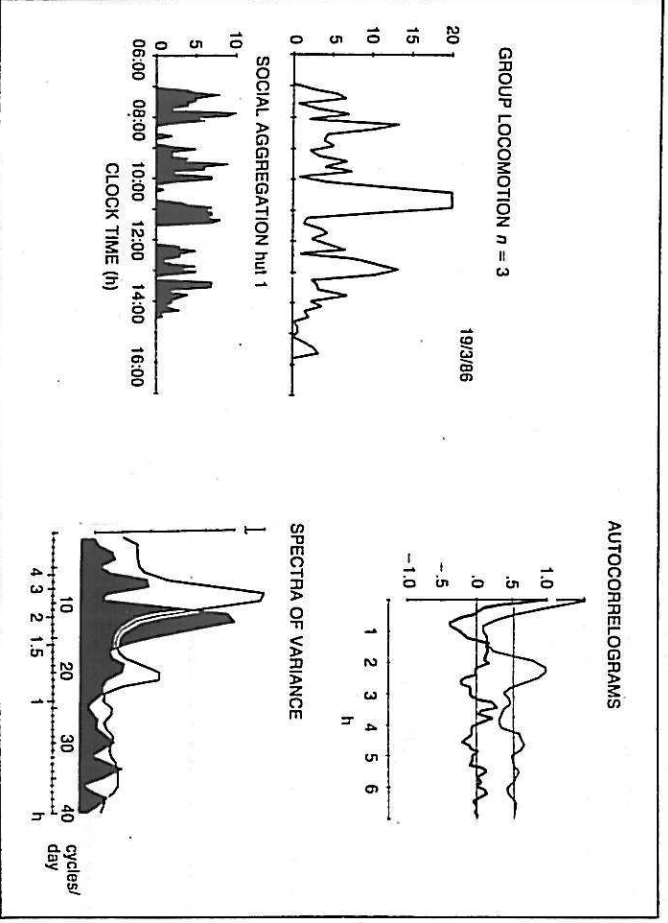
Fig.6   Time series, autocorrelograms and spectra of group locomotion and social aggregation determined during four days of observation

subjects

Individual Oscillators

Locomotor Activities

night   day   night
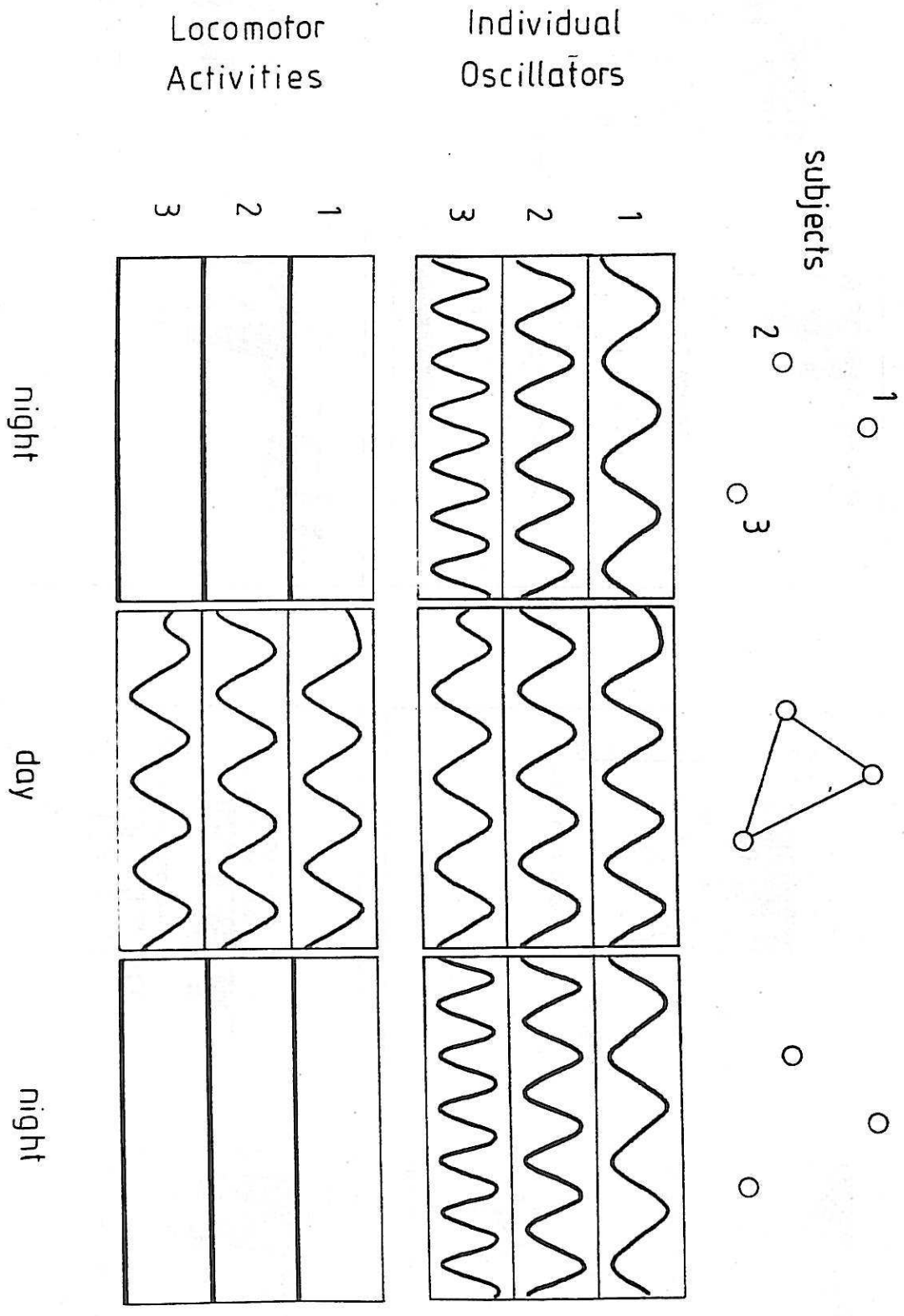
Fig. 7   Sketch above: hypothesized endogenous oscillators of three individuals as they run during night and day time. During daytime, the oscillators are coupled to one another. Sketch below: individual locomotor activities modulated by endogenous, synchronized oscillators during day time, but disappearing during the night.

Pool of exciting neurons

(X-cells)

Pool of inhibiting neurons

(Y-cells)

self – inhibition

self – excition
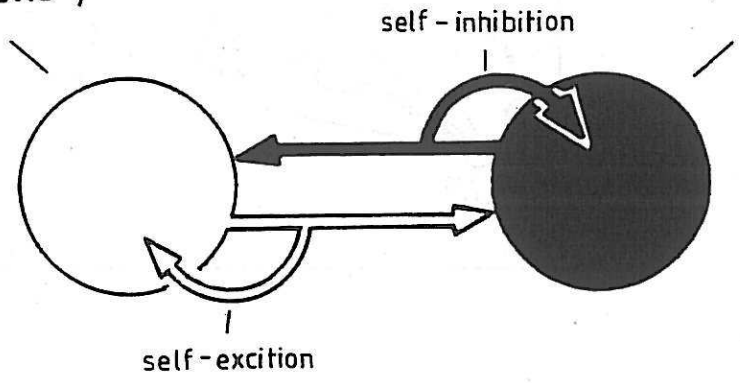
Pooled neuronal activity of X- and Y-cells

X–

-Y

time
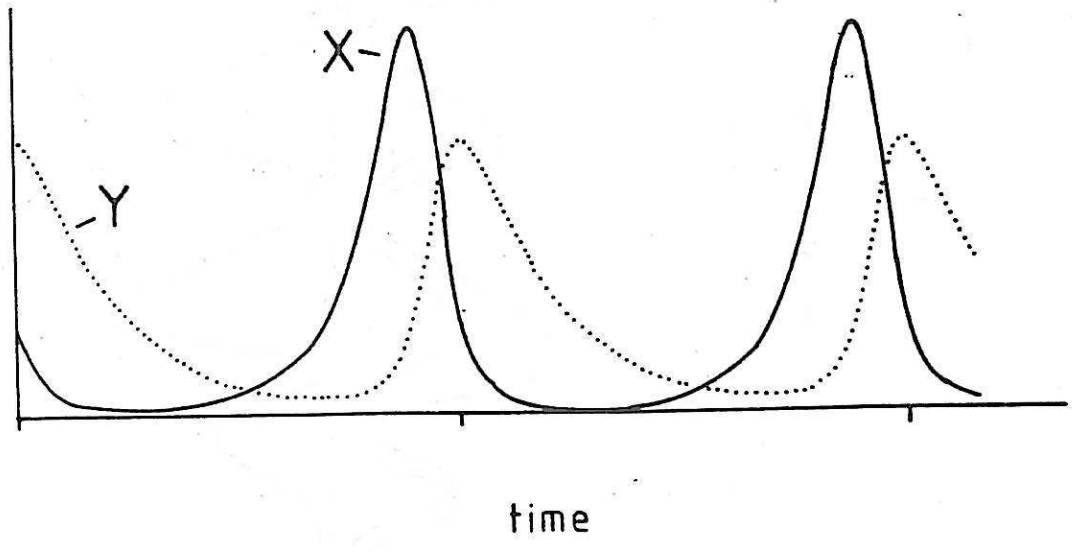
Fig.8 General scheme of a hypothesized neuronal oscillator system generating ultradian cycles of its functional components X and Y representing neuronal discharge activities.

a)

b)

c)

time of day →

t
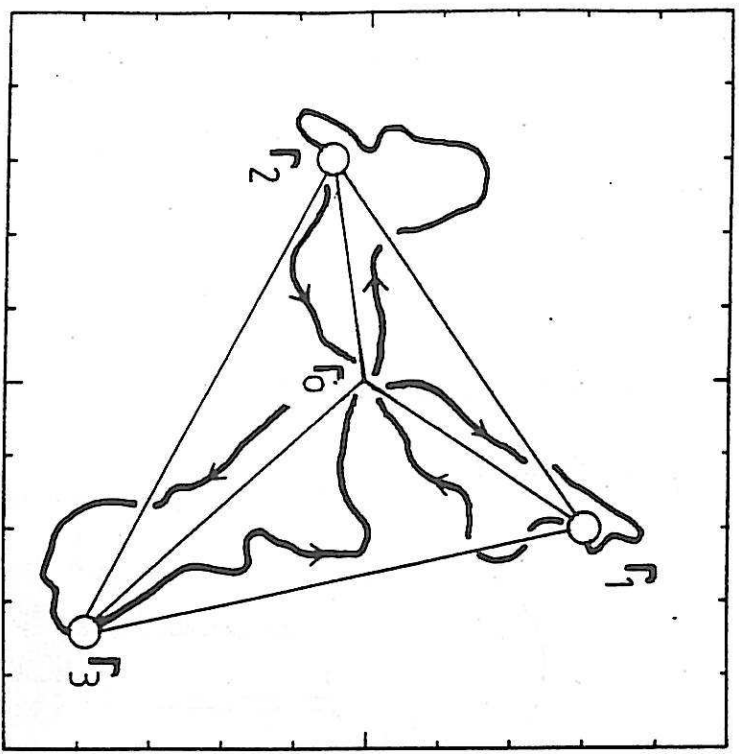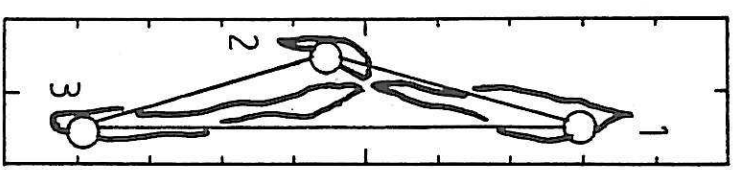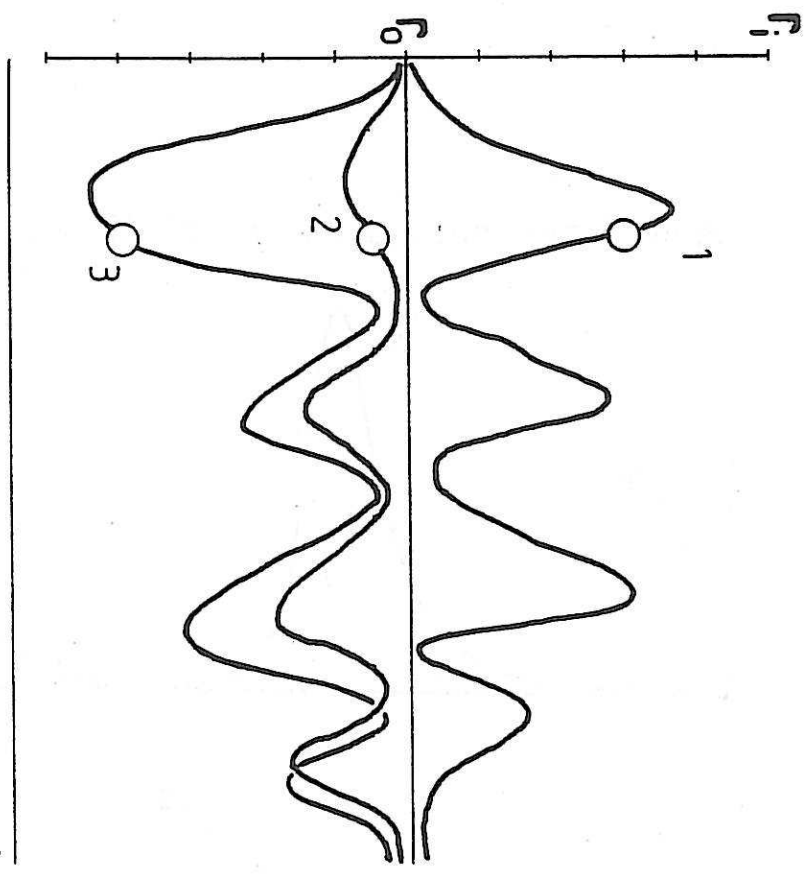
Fig. 9 a) Two-dimensional sketch of three individual traces of movements. b) one-dimensional
sketch of individual traces. c) sketch of space-time diagrams of the one dimensional model.
ri = position vector of the ith individual. ro = position vector of the center of the village;
thin lines between points of positions = attracting forces between individuals and to the
center of the village ('elastic strings').
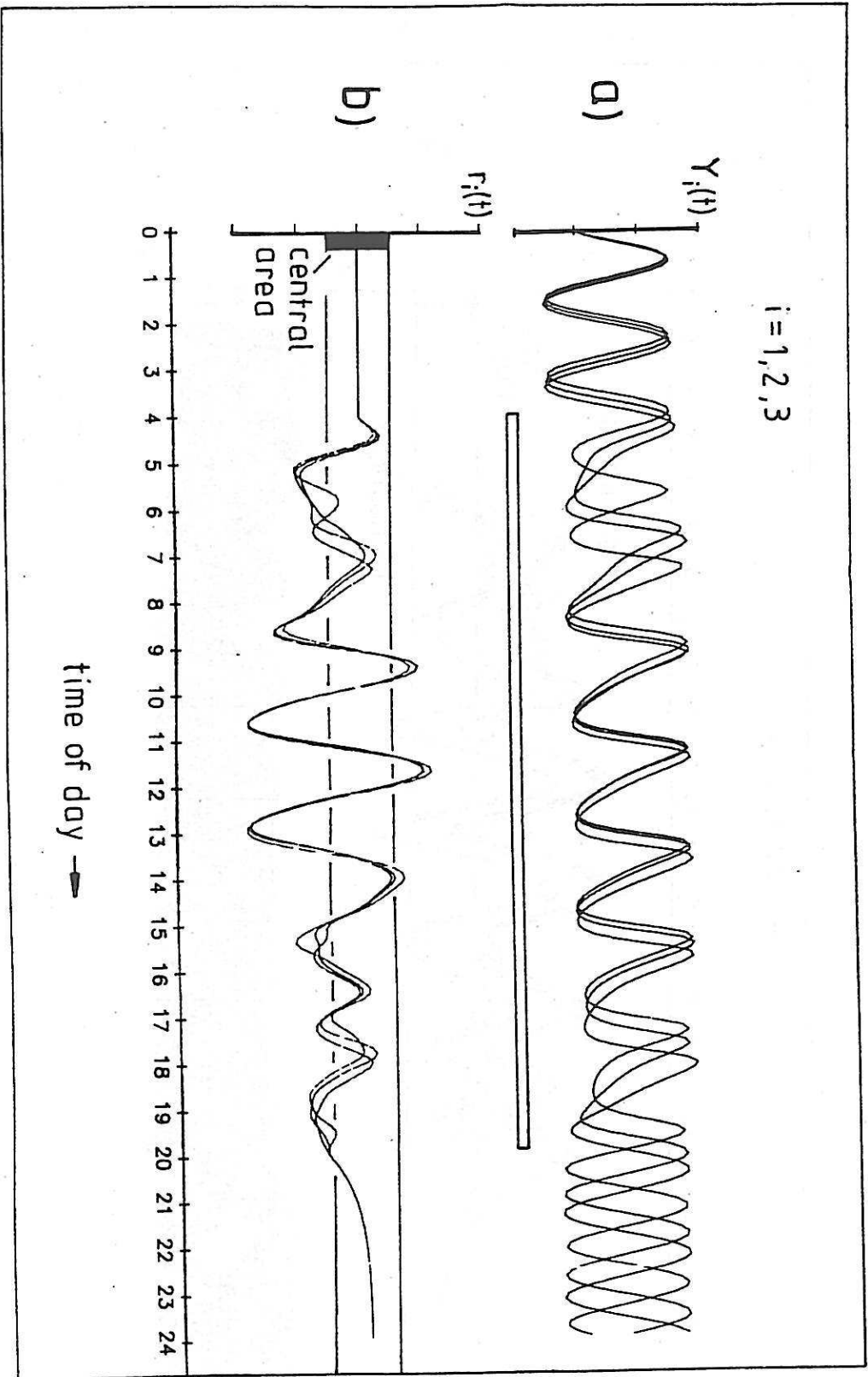
Fig.10 a) Oscillations of three Y-components simulated by the proposed computer model. White bar: duration of social coupling. b) Corresponding space-time diagrams of individual movement around the center of the village. $r_i(t)$ = position of the i-th individual.
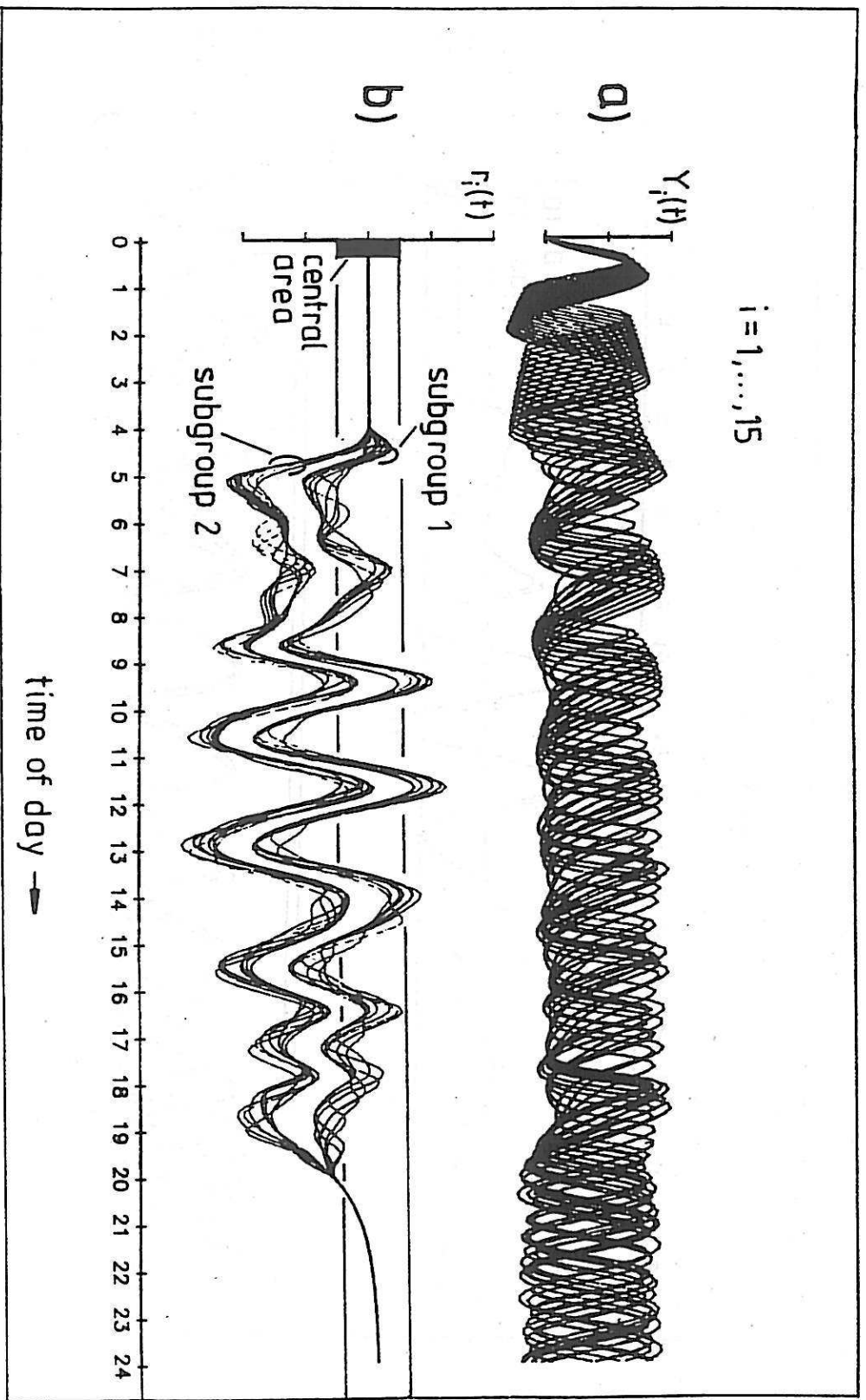
Fig.11 Y-components of an assembly of 15 oscillators (a) and corresponding space-time diagrams as simulated by the one-dimensional model
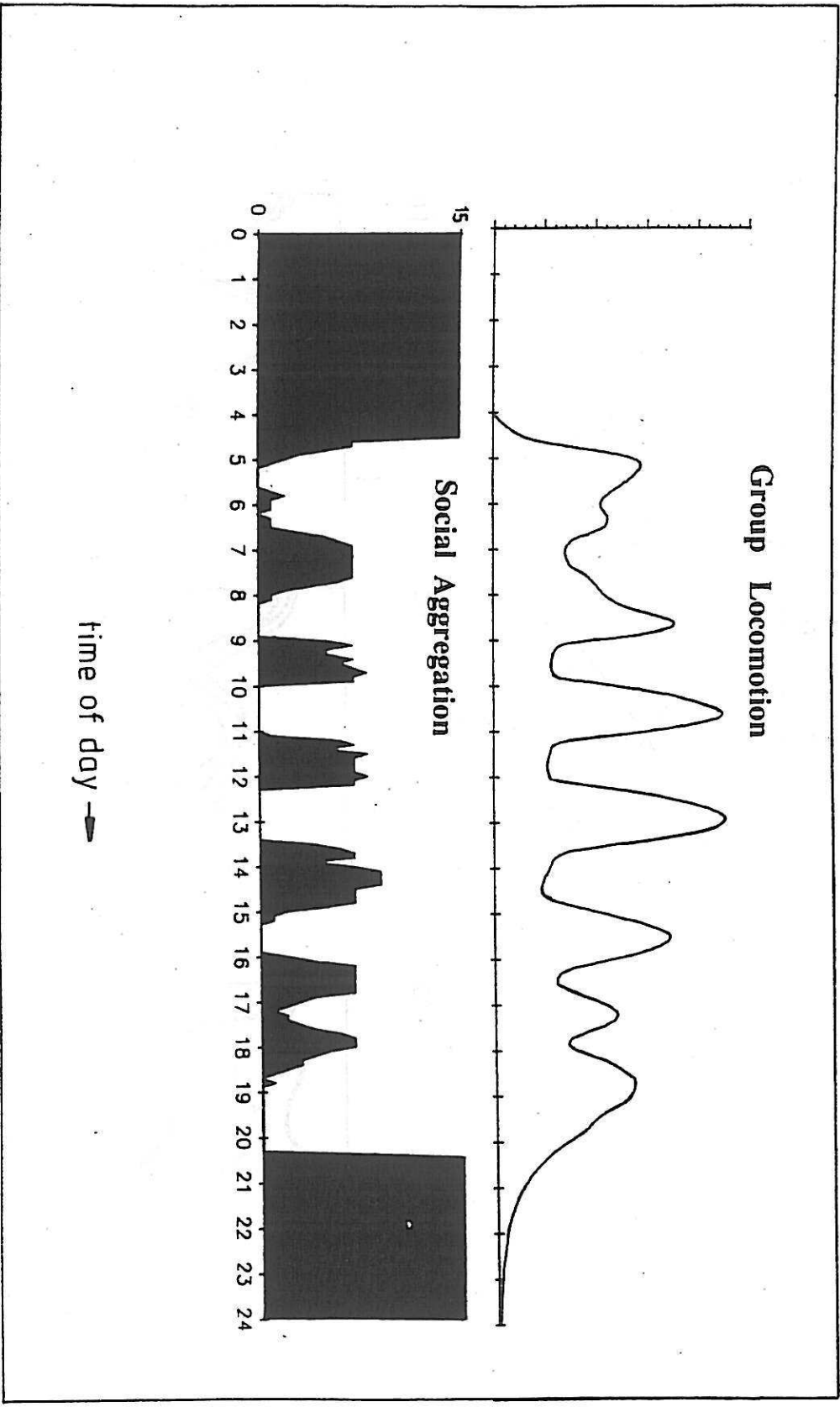
Fig.12 Averaged group locomotion (diagram above) and social aggregation (diagram below) corresponding to the system of 15 individual oscillators.
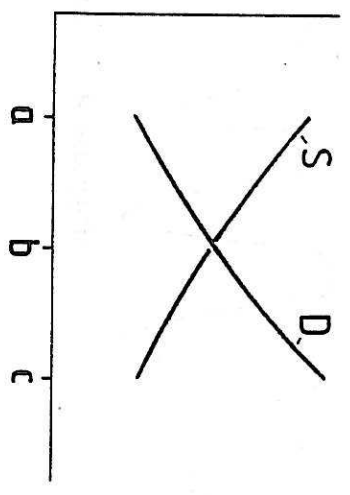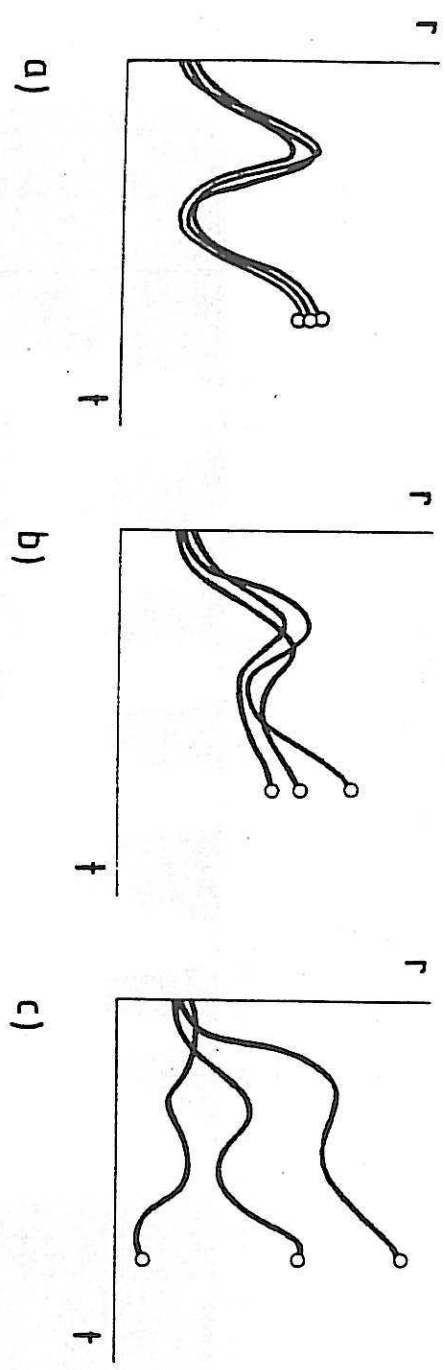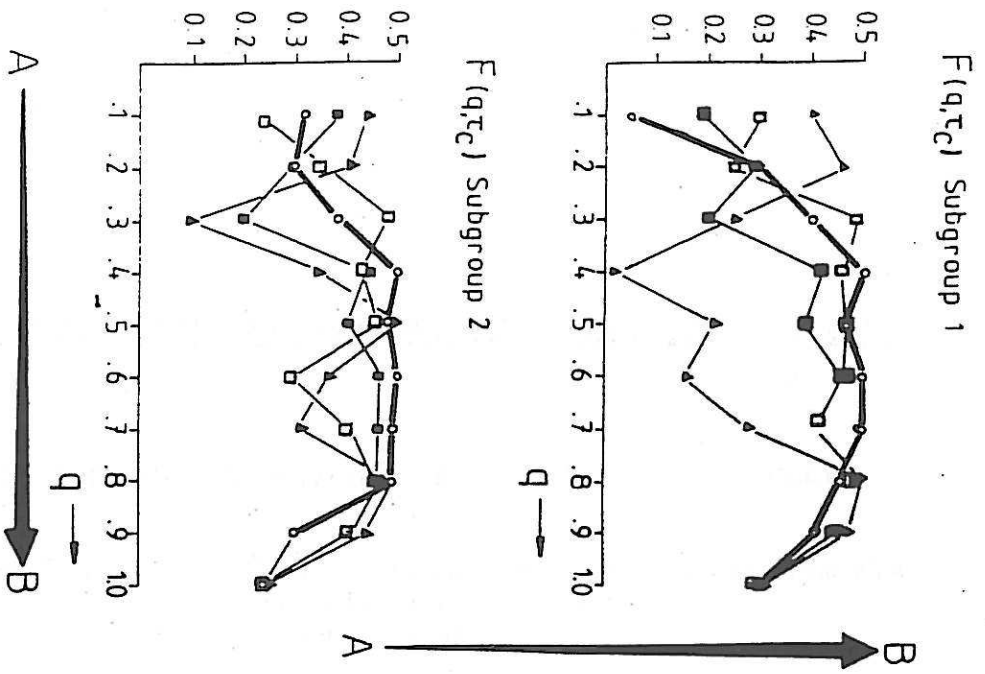
Fig.13 Sketches of three space-time diagrams for several distributions of oscillator periods indicating a decreasing synchrony, but an increasing diversity from situation a to c, as shown by the sketch below.
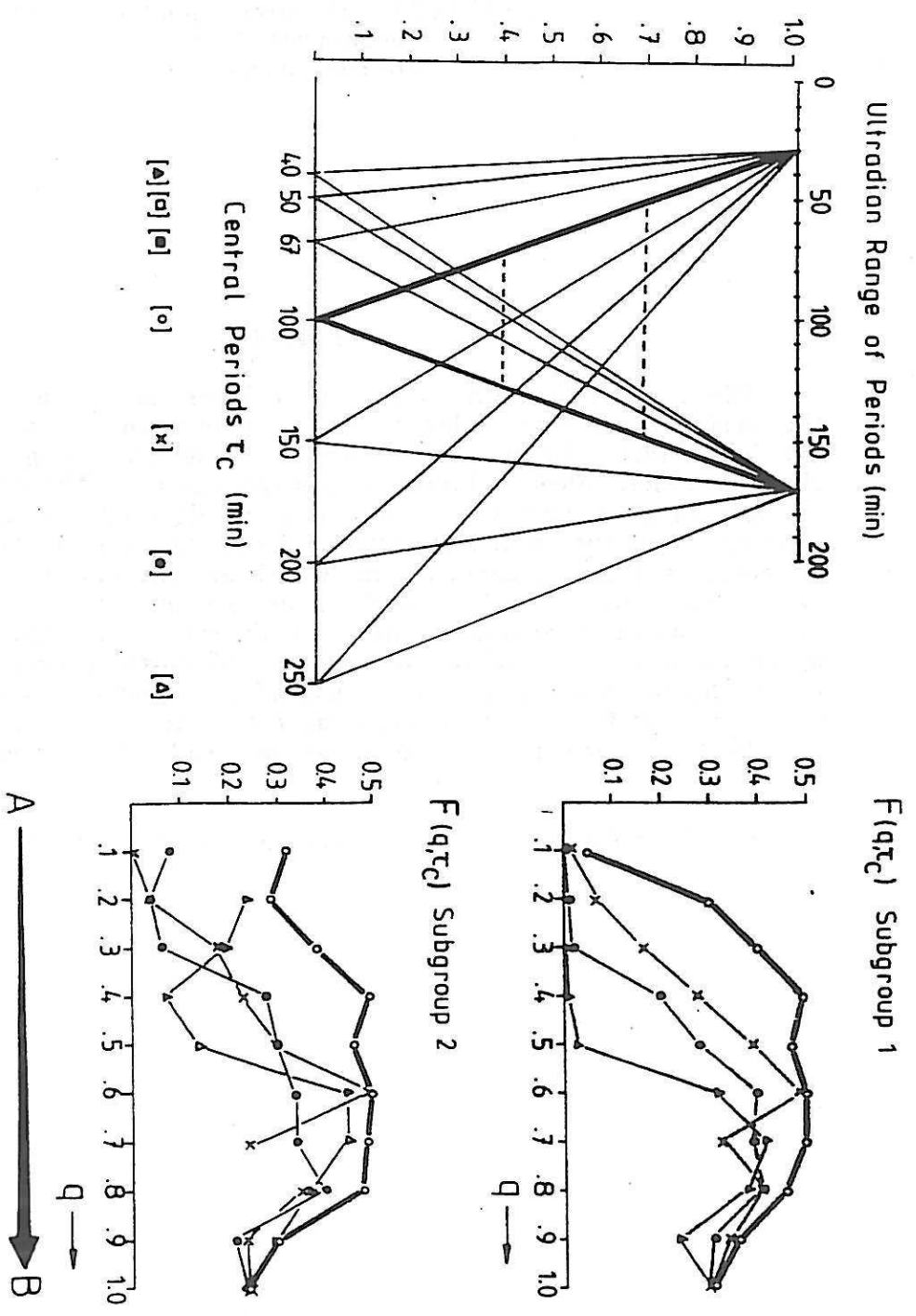
Fig.1.1 Diagrams of the function F determined for two subgroups of space-time portraits generated by eleven particular distributions of 15 ultradian periods. Each distribution was centered around one of seven central periods ($t_c = 40, 50, 67, 100, 150, 200$ and 250 minutes) and linearly widened according to the parameter q (middle diagram). a) Diagrams of F as a function of the width parameter (q) and central periods shorter than or equal to 100 minutes. b) Corresponding diagrams for central periods greater than or equal to 100 minutes. Note that vales of F determined for the central period of 100 minutes and a width indicated by q-values of 0.4 - 0.7 exceed F-values calculated for alternative distributions.