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A Concept on Mechanisms of the Endogenous Daily Rhythmic Activity

By

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When animals are kept under constant environmental conditions, at least in regard to light and heat, they exhibit various kinds of modifications in behavior. Some may be completely disturbed and show unrhythmic activities[1], but others may continue their original rhythmic activities as long as 100 days or more, though the activity-phase may not always be the same with that of the natural day-night rhythm (e. g. the sea-pen, *Cavernularia obesa*; Mori, 1947)[2]. By comparing many such cases we recognize various transitory modes among them (Mori, 1945–2).

In this paper I intend to propose an opinion[3] with respect to the mechanisms of well established endogenous rhythmic activity. Before describing the conclusion, several premises and assumptions are neccessary.

Premises: 1) All vital phenomena exhibited in the animal body are related more or less with some chemical reactions (both reversible and irreversible). 2) The Le Chatelier's Principle, the Law of Mass Action, and the 1st and 2nd Laws of Thermodynamics are applicable to all these reactions. 3) The number of these reactions are finite. 4) Animal behaviors (of course including daily rhythmic activity) are evoked on the bases of these chemical reactions. These four premises, I believe, will be admitted without any serious objections by zoologists.

Assumptions: 1) All chemical reactions going on in the animal body may be correlated and harmonized with each other, as in the case of the toothed wheels of a watch. 2) If the balance of a certain set or a series of chemical equilibriums is lost by some causes and the transition of the equilibrated state is evoked, it will instantly effect on

1) This sort of mode will be called after Park (1940) as the "exogenous rhythmic activity".

2) This sort of mode will be called after Park (1940) as the "endogenous rhythmic activity".

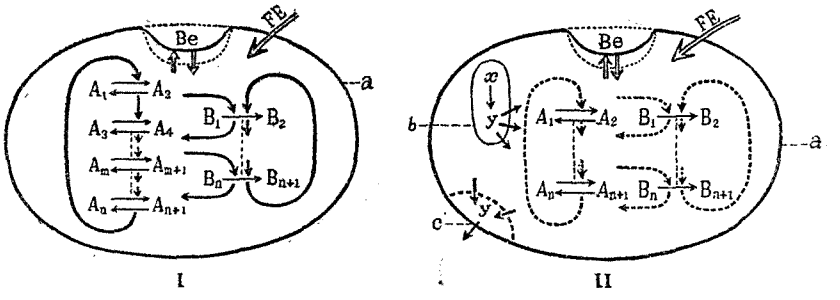
3) Preliminary report concerning with this opinion has already been published in my previous paper (Mori, 1945-1, 2), and this is the further development of it.

the next set or series of equilibriums and causes the transition of it, or influence the velocity of a certain irreversible reaction. The effects due to these changes gradually extend over the whole system of chemical equilibriums. 3) If all these series of changes take place rhythmically day by day, their exterior manifestation may be the daily rhythmic activity.

Here I wish to quote some instances showing the transitions of chemical equilibriums in the animal body. According to Hecht and Wald (see Heilbrunn's Text-book, 1938), the photoreceptors of animals contain some photosensitive substances and these are broken down by light into several materials which initiate the nervous responses. Hecht's shema is "$S \rightleftarrows P+A$". The rate of breaking down of this photosensitive substance "S" is constant at a certain intensity field of light. This reaction is reversible, "P+A" is united to form "S" at a constant rate at a certain intensity of illumination, so the balance of reaction is attained in every light field. There is another good instance in the metabolism of living muscles. In this case several kinds of reversible and irreversible reactions are concerned (see Kato's Text-book, 1931 and Heilbrunn's Text-book, 1938). These transitions of equilibriums, of course, influence other chemical reactions, and as the result they give remarkable effects on the behavior of animals. I think that numerous series of such reactions are participated in the manifestation of a routine daily rhythmic activity of an animal body in complete harmony and close combination with each other. Now, this may be the place to propose my hypothesis.

Hypothesis: Two fundamental schema may be considered in which chemical reaction series are repeated rhythmically day after day under constant environmental conditions.

a: The first is the case in which many chemical reactions occur one after the other with slight phase differences and stimulating each other, thus forming a cyclic system. In this system may be comprized various reversible ("A" series in Text-fig. 1) and irreversible ("B" series in Text-fig. 1) chemical equilibriums. At a certain moment, in these reversible equilibriums, when the material "A_n" has just attained a certain amount, transition of balance "$A_1 \rightarrow A_2$" occurs, and increase of the material "A_2" causes the next reaction "$A_3 \rightarrow A_4$". Sometimes the irreversible reaction "$B_1 \rightarrow B_2$" is induced and this stimulates the transition of the equilibrium as "$A_5 \rightarrow A_6$". The same process applies correspondingly to the following reactions, and when the last set of reaction "$A_n \rightarrow A_{n+1}$" proceeds, it stimulates again the first set of



Text-figure: Schematic representation showing the mechanisms of the endogenous rhythmic activity.

A: reversible chemical reactions. B: irreversible chemical reactions. a: animal body. b: periodic discharge of "y" factor. c: excretion of "y" factor. Be: rhythmic behavior. FE: intake of foods as the energy sources. Other explanations see text.

equilibrium and "$A_1 \leftarrow A_2$" occurs. Thus the opposite series of transitions can be induced and at last the reaction "$A_n \leftarrow A_{n+1}$" occurs. By this way the transition of equilibrium will be able to accomplish its one cycle. These may be the simplest course to be considered, and in nature many more complicated ways are surely expected. In some case, even if the same material, e.g. "A_m", reaches a certain amount, its effects may be different according to the history of the reactions, i.e., either it has been accumulated by "$A_m \leftarrow A_{m+1}$" transition or decreased gradually by "$A_m \rightarrow A_{m+1}$" transition. In another case, some kinds of animal behavior may be evoked on the way of these transitions and it may influence the following sets of reactions. If these cyclic phenomena do not easily alter their rhythmic repetitions, they mean the development of the endogenous rhythmic activity. If we search for some physical models, the case of the electric oscillator with complicated amplifers may occur to our minds. But the complexity of this apparatus can of course not be compared with the mechanism of rhythmic animal behavior.

b: Second is the case in which intermittent phenomena are concerned (Text-fig. II). In this case chain reactions as mentioned above cannot continue cyclic repetitions by themselves because of their less intimate interrelations, and in order to repeat the rhythmic life the special irreversible reaction "$x \rightarrow y$" is necessary, whose velocity of reaction is nearly constant. When "y" is accumulated to a certain amount in some place of the animal body, sudden discharge occurs and by this stimulation one series of chemical reactions start out. In consequence of the gradual decrease of "y", which may be caused by excretion or

by other reasons, the original equilibrium state is gradually recovered, thus accomplishing one cycle of activity. Therefore, the daily rhythmic phenomenon must depend on the regular discharge of "y". As a model of this type may be consider continuous secretion of hormones ("y" factor) from gland cells ("x" factor) and sudden discharge of it (discharge of "y" factor). Relation between daily rhythmic activity of the sea-pen and daily change of $H^{\cdot}$ concentration in the body fluid may be explained by this hypothesis. $H^{\cdot}$ is produced incessantly as the effect that the cells of the sea-pen are "living" and the abrupt discharge of "y" factor (in this case abrupt dilution of $H^{\cdot}$ concentration) takes place automatically by the expansion of the animal body (Mori, 1945–1, 2). If we seek for some physical models bearing resemblance to this type of intermittent phenomenon, the sudden discharge of water by siphon mechanism or the gyser mechanism may be quoted[4].

Two cases mentioned above are, of course, the fundamental modes, and in nature they may be cooperating together in various manners. Be that as it may, the animal seems to be able to continue its own daily rhythmic activity under constant environmental conditions through these sorts of phenomena, and this hypothesis will be understood by accepting that the premises and assumptions mentioned above hold in the reactions going on in the animal body.

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4) Some physical treatment about this mechanism has been attempted by Fudiwara (1940).