

ON THE MODIFICATION OF TEMPERATURE CHARACTERISTICS.*

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I.

An endeavor to find if specific meanings might be attached to the temperature characteristics of vital processes has led to the view¹ that common activities of organisms appear to be governed by the velocities of members of a system of chemical reactions, identified to the extent that they yield quantitatively concordant critical increments, which are repeatedly encountered in very different kinds of living matter (Crozier, 1925-26). Experimentally determining which of several possible critical increments a given phenomenon shall be made to exhibit thus signifies control of specific governing reactions (Crozier and Stier, 1924-25, *a*), and makes possible, even without great regard for the theory giving rise to it, a new type of analysis. Its development is facilitated by knowledge of instances in which it is possible to modify the temperature characteristic, even when no truly reversible determination may be attained.

Several quite different possible kinds of modification can be predicted to occur, on the basis of what is already known of the temperature relations. It will be shown that some of these possibilities are realizable. They may be roughly enumerated:

(1) The velocity or the latitude of variation may be changed without change of increment; (2) a normal temperature characteristic

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¹ Cf. papers in *J. Gen. Physiol.*, vols. vii, viii, ix (Glaser, Orr, Cole, Morrison, Hecht, Crozier, and others).

may be slightly increased, or decreased; (3) it may be changed to a quite different value, either obviously composite² or numerically equivalent to one already familiar in other essentially homologous processes; (4) a rectilinear relation between *log velocity* and $1/T$ K may be changed to a curve; (5) a break in the temperature graph, with two critical increments over two ranges of temperature, may be

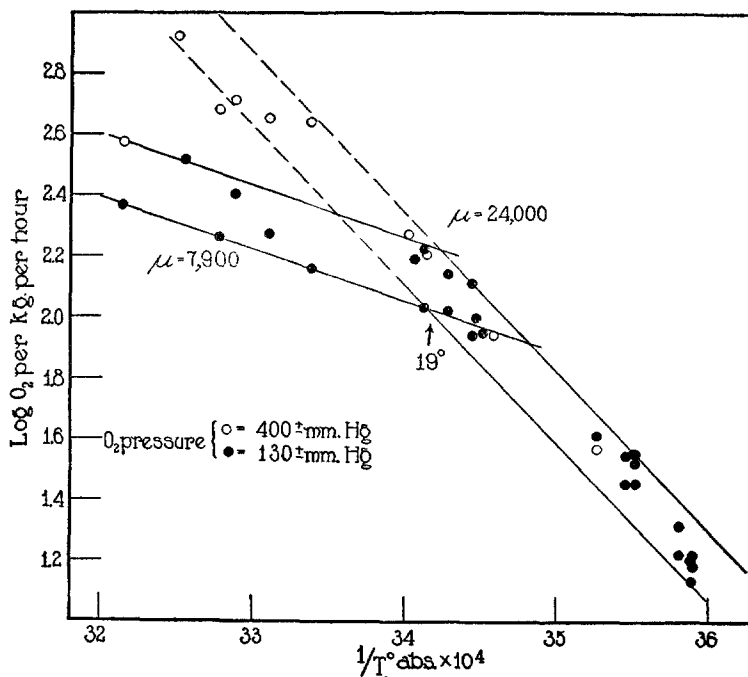


FIG. 1. At low oxygen pressures, the temperature characteristics for velocity of oxygen usage by leeches are $\mu = 7,900$ and $\mu = 24,000$. When the oxygen pressure is increased the break is obliterated. Data from Pütter (1914).

obliterated; or one may be caused to appear in a previously unbroken line; (6) a break of the sort described for breathing rhythm of anurans

² Thus when it was sought to study the temperature coefficients for the action of digitalis alkaloids upon the heart (frog; Sollmann, Mendenhall, and Stingel, 1914-15) the Q_{10} ratio was found to be very high. The value of μ in the Arrhenius equation which fairly well fits these data is about 40,000. This seems due to the fact that the activity of the heart, as well as the temperature, controls the speed of the toxic action.

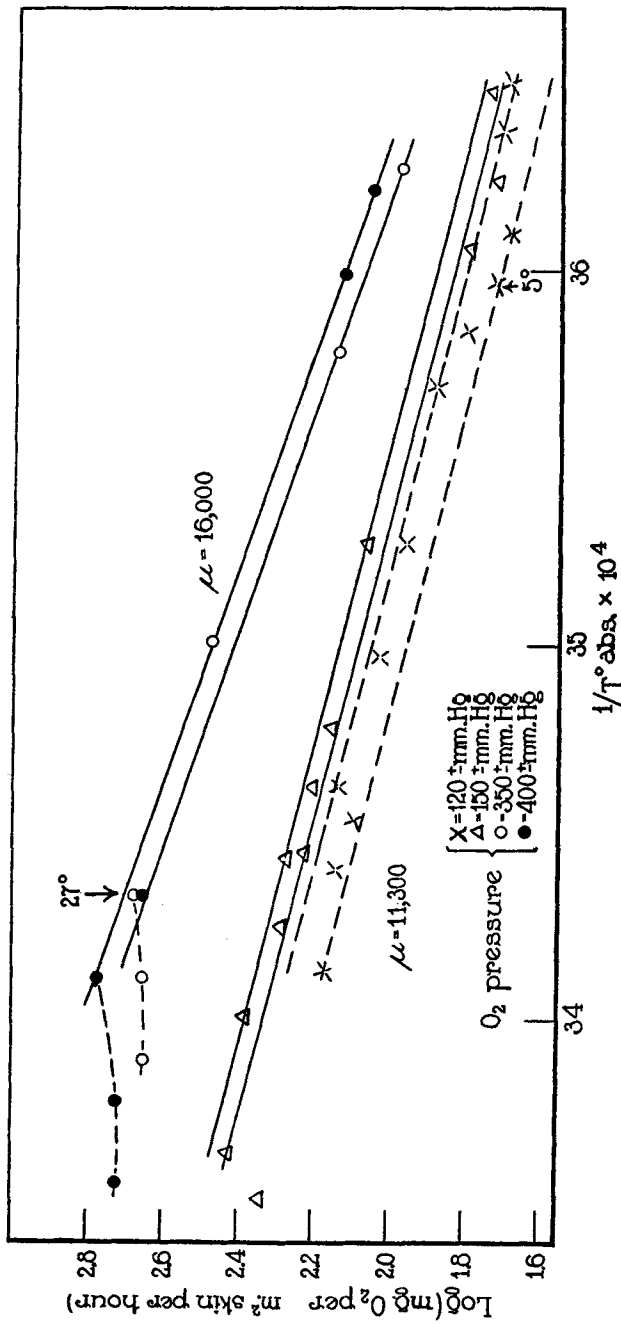


FIG. 2. Variation in μ for velocity of oxygen utilization (via skin) in frogs at different temperatures, when the oxygen pressure is changed. Data from Pütter (1914). The increments fairly assignable belong to the two sorts commonly found for respiration. (Below 5° the observations at 350 mm. O_2 pressure are irregular.)

(Crozier and Stier, 1924-25, *b*), signifying change of velocity without change of increment, may be obliterated; or one may be developed; (7) the type of change mentioned in (6) might be combined with a change of increment.

Alterations of types (1), (3), (4), and (5) are already known. Change of type (4) is readily obtained if due time for recovery is not allowed following exposure of the organism to very high or to very low temperature, and in certain types of toxic action (*cf.* Crozier, 1924-25). In addition to instances given in previous papers¹ certain other illustrations taken from cases in the literature of temperature coefficients may be cited here (Figs. 1, 2); they do not exhaust those available.

We desire to record some new instances of this sort, calling attention particularly to the fact that when change of increment is induced by experiment the new value is in each case that of an increment already known to be of frequent occurrence and known to be related to, or in some way organically connected with, the initial value. In doing this we give details of single experiments, that is records pertaining to individual organisms, without describing similar confirmatory instances. Experience shows that it is most important in such work to obtain numerous measurements upon single organisms.

We also describe, in greater detail, an experiment of more definite kind dealing with reversible control of the increment for heart beat frequency in *Limax*.

II.

The temperature characteristics for frequency of pharyngeal breathing movements of frogs is of the order $\mu = 8,500 \pm$ (Crozier and Stier, 1924-25, *b*). As an instance of the concordance among values of μ obtained from homologous activities, it may be added that this value also holds for the frequency of rhythmic gill contractions in larval *Amblystoma*. (The same magnitude holds after destruction of the forebrain of the salamander; we intend to describe these experiments separately.)

Destruction of the forebrain of the frog usually results in temporary acceleration of the breathing rhythm, followed by its very gradual decline. This was studied by means of frequent series of observations, over the temperature range, in a number of preparations, for periods

up to several weeks. The method of observation is described in a previous paper (Crozier and Stier, 1924-25, *b*).

It was earlier shown that the adjustment of frogs to laboratory temperature involved the disappearance of a tendency to pronounced decrease in frequency of pharyngeal movements, without change of

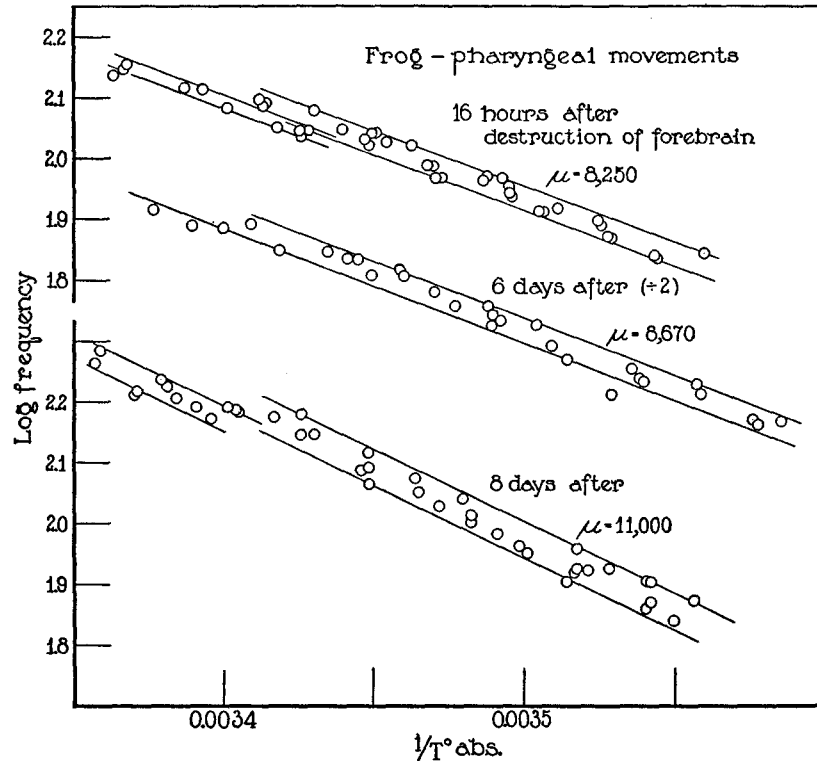


FIG. 3. Frequency of pharyngeal breathing movements in Frog 3, at intervals after destruction of the forebrain. The plotted points are averages of concordant readings.

increment, at temperatures above 15° . This result can be paralleled by other temperature relations in frog tissues, and there seems no doubt of its reality. One effect of decerebration is to cause its more or less abrupt reappearance. For some days following decerebration the best assignable temperature characteristic remains $8,500 \pm 200$ (Fig. 3). The latitude of variation at given temperature is fairly

constant for each individual. About 8 days after destruction of the forebrain, in some cases, the increment is definitely altered. It now becomes $\mu = 11,000 \pm 50$, and the character of the break is changed (at least temporarily). The change appears later in other instances. At this time the frequency of pharyngeal breathing is detectably increased, at given temperature. Later the break already referred to may become very pronounced, without, in our observations, any

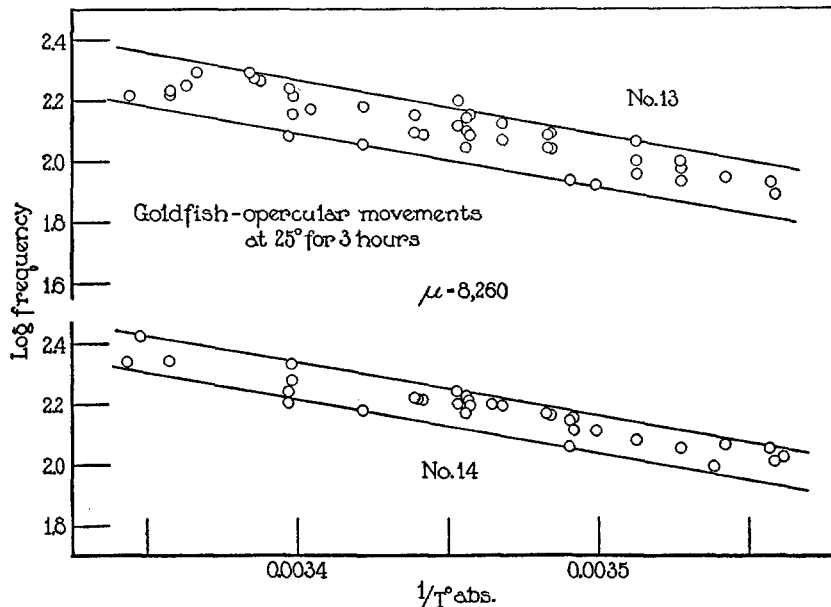


FIG. 4. Frequency of opercular movements in two goldfish following 3 hours exposure to a temperature of 25°. The plotted points are single observations. No. 13 showed constant gentle movements of the pectorals; No. 14 was quiet, with no fin movements.

further change of increment. We are not yet able to decide the exact mode of transition from $\mu = 8,500$ to $\mu = 11,000$, but we are confident that it does not involve a *gradual* upward tendency.

This sort of change of increment is not so convincing, by itself, as a similar one already described in grasshoppers (Crozier and Stier, 1924-25, *a*), where the sequence of changes in μ following decapitation is 7,900, 16,200, 11,200. We are able to add, however, one other instance among vertebrates in which the increment 8,000+ appears in

connection with an activity for which $\mu = 16,500$ is characteristic. Two experiments with goldfish are given in Fig. 4. They show that it is possible to produce for opercular movements, instead of the increment 16,500, the value 8,300. This was accomplished by exposing the animals, previously ascertained to yield $\mu = 16,500$ for frequency of opercular rhythm, to a temperature of 25° for 3 hours in water with oxygen content of about 3 cc. per liter. The increment 8,300 persisted for some hours after this treatment.

Thus in the breathing rhythm of vertebrates the increments 8,000+, 11,000+, 16,000+ seem definitely associated, in such a way as to make possible their experimental interconversion. The evidence from experiments with grasshoppers shows a similar system of processes to be controlling the frequency of breathing movements. It may be added that experiments with the rhythm of the book-gills of *Limulus* (Crozier and Federighi³) confirm this generalization so far as it relates to $\mu = 8,000+$ and 16,000+. The respiratory movements of *Sepia*, according to some rather fragmentary data of Polimanti (1912), show $\mu = 11,000 \pm$.

III.

In commenting upon the temperature characteristics for heart beat frequency in molluscs, it was pointed out (Crozier and Stier, 1924-25, *d*) that this quantity differed in several good series of data for different species, but that the values of μ seemed to be members of an organically connected series frequently represented in vital processes and particularly associated with respiration (Crozier, 1924-25). Values of μ obtained by Glaser (1925-26, *b*) strengthen the basis for this hypothesis.

Attention was called to the fact that among pulmonates there seemed to be evidence of seasonal alteration in μ . This invited further attempts to modify, predictably, the magnitude of the temperature characteristic for heart rate in *Limax maximus*. Experiments during March, 1925 (in New Jersey), gave for *Limax* hearts $\mu = 16,300$. A series of tests with animals freshly collected from a greenhouse late in December, 1925 (at Cambridge), gave uniformly

³ Unpublished experiments on *Limulus*.

$\mu = 11,500$. The technique was similar in both series of observations. The animals were each placed at the center of a rather snugly fitting long glass tube connected at one end to the outside air and at the other to a suction pump. At intervals, between readings, the air in the tube was renewed with outside air (first brought to thermostat temperature). By means of a lens of 8 inches focal length light from a pro-

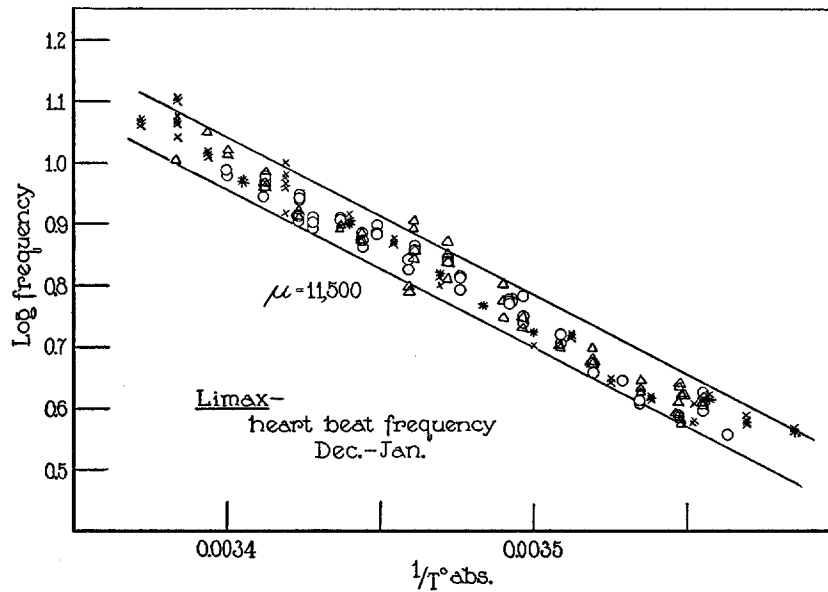


FIG. 5. Heart beat frequency as controlled by temperature, in *Limax* during December and January. Three individuals. The latitude of variation corresponds, at the highest temperature, to a variation of 1.35 sec., at the lowest temperature to 5.5 sec., in the time for 10 beats. Above 25°, and below 9–10°, the animals are very difficult to keep quiet; with changes in peripheral tension the heart frequency rises. The plotted points are single observations, from three animals (different symbols), brought together for comparison by the multiplication of the observations for two of the animals by a factor.

jection lantern, after passing through an infra-red filter, was concentrated upon the region of the heart of each *Limax*. The tubes containing the animals were immersed in a water thermostat with parallel glass walls. By this arrangement, the heart beat can be seen with little or no difficulty. It is absolutely necessary that the

slug be motionless, with tentacles retracted, if any regularity is to be expected in the variation of the heart beat with temperature. Other things equal, the frequency of heart beat varies with size of the animal, smaller animals having a higher rate. Otherwise, no significant individual differences are found.

The two magnitudes, 16,300 and 11,500, agree quantitatively with those calculated for cardiac rates in the mussel *Anodonta* (11,200; Crozier and Stier, 1924-25, *d*, from Koch, 1916-17), the heteropod *Pterotrachea* (11,200 \pm 500; Glaser, 1925-26, *b*), and in the pteropod *Tiedemannia* (16,200 \pm 200; Glaser, 1925-26, *b*). There is evidence of their occurrence in *Helix* (data of Lang, 1910, in Crozier and Stier, 1924-25, *d*). They represent temperature characteristics or critical increments of processes commonly found associated with respiratory movements among arthropods (Crozier and Stier, 1924-25, *a*, grasshoppers; Crozier and Federighi⁸) and in the goldfish (Crozier and Stier, 1924-25, *c*), and which appear to be specifically implicated in respiratory metabolism and in phenomena assumed to be directly dependent thereon (Crozier, 1924-25, *a*; Glaser, 1924-25, *a*; Orr, 1924-25).

On the assumption that seasonal metabolic differences, connected with hibernation, may modify the temperature characteristic for heart rate in such pulmonates as *Helix* and *Limax*, it was sought to control this modification by the injection of sugar solution. The experiment is particularly interesting in the case of *Limax*, for after the ingestion of sugar there is independent evidence of a definite neuromuscular effect, namely the (reversible) suppression of phototropism (Crozier and Libby, 1924-25). But it is of course not to be presumed that the (central nervous ?) inhibition of phototropism connotes necessarily a central nervous effect which would inevitably be the one reflected in the (neurogenic ?) heart rhythm of *Limax*.

During the winter months *Limax* sufficiently large for these experiments are very difficult to obtain, due to hibernation, and only small numbers could be obtained from greenhouses. Those so obtained are distinctly less active at room temperature than is typical in spring. It is to be supposed that the nutritive level of such winter animals is distinctly lower than during warmer months. Certainly they eat less. Significant changes in reducing power associated with the state of nutrition are known to occur in the body fluids of other inverte-

brates (Morgulis, 1921; Hemmingsen, 1924), and presumably occur in *Limax*. We have ascertained that the Cu-reducing power of *Limax* blood is increased after ingestion of carbohydrate.

By moistening the lips of a slug with sugar solution, the mouth and pharynx are caused to open, so that the tip of a pipette may be

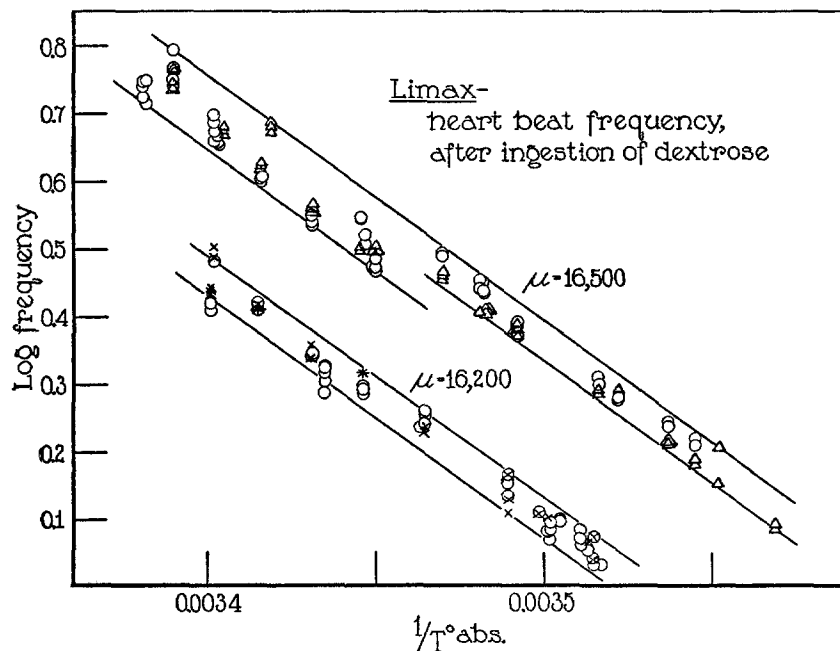


FIG. 6. Two sets of readings on each of two individuals, 6 to 24 hours after ingestion of $0.4 \pm$ cc. M/5 dextrose. The development of an increased latitude of variation above 15°C . is more or less characteristic.

inserted for some distance. In this way 0.5 cc. of M/5 dextrose was placed within the alimentary tract. In the course of a few hours, during which the heart rate is very irregular, in correlation with muscular movements, the animals, which previously were negatively phototropic, become indifferent to light. Determinations of the temperature effect on the heart were begun about 6 hours after the ingestion of sugar. The effect of the sugar in connection with the heart apparently lasts for several days, but negative phototropism returns after about 48 hours.

The following account is based especially upon series of readings of heart beat frequency at different temperatures in two individuals most extensively used. The plotted points (Figs. 6, 7) are single observations, not averages. The total number of readings was 740.

Preliminary determinations (Fig. 5), four independent series on different days, gave $\mu = 11,500 \pm 250$. The last of these series was

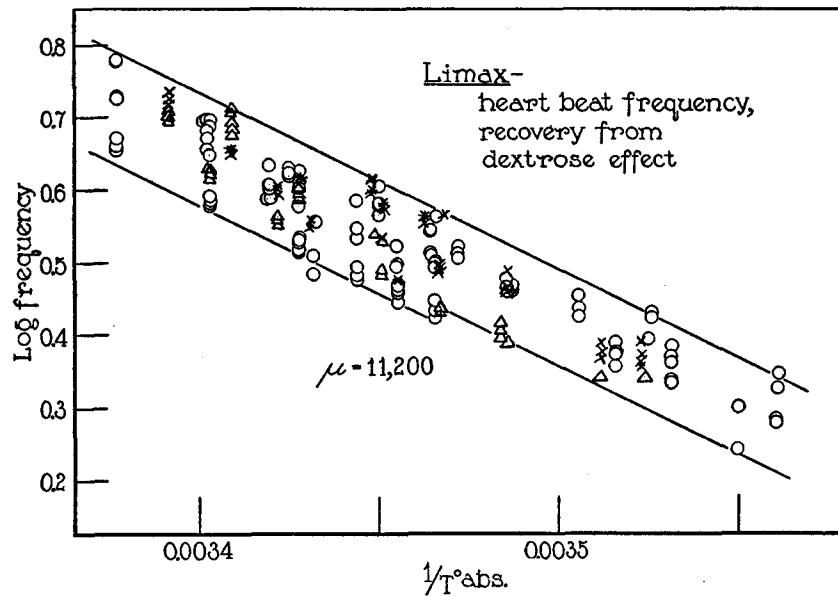


FIG. 7. Observations from the individuals involved in Figs. 5 and 6, showing recovery from temporary manifestation of $\mu = 16,200$ for heart beat frequency and the resumption of the value typical for the winter condition. The latitude of variation is greater than at the beginning of the experiment.

obtained on January 6, 12 days after the first. Thus there is a good indication of a definite, uniform value of the temperature characteristic under these conditions.

During 1 to 2 days after feeding the result of six series of observations, three on each animal, gave uniformly $\mu = 16,200 \pm 320$. This agrees quantitatively with the value previously obtained with active animals in late spring.

The probability is therefore great that one has in this case accomplished a definite alteration of the processes governing the frequency of the heart beat, of such a character as to experimentally

bring into a position of control one of two processes known to be associated in the matter. That the particular increment expected in this instance is in fact the one to appear is the best possible evidence that temperature characteristics correspond to discrete phenomena in living matter, which may in this way be classified and possibly identified as to their chemical nature.

IV.

The question at once arises: Is the effect of the sugar ingestion reversible? There are two possibilities. Either the animal is permanently aroused from its semiestivation, or the effect on the heart beat is due merely to a temporary metabolic disturbance. In the latter event the demonstration of experimental control of the temperature characteristic is just so much neater. But the former possibility would not affect the interest of the change from one specific value to the other.

The increment 16,300 consequent upon sugar ingestion does in fact disappear, and within at least 4 days the temperature effect on the hearts in these experiments reverts to the initial value, 11,000+. The actual magnitude obtained 6 days subsequent to sugar ingestion is $11,200 \pm 300$, in four series of measurements (see Fig. 7).

V.

SUMMARY.

In December and January the frequency of heart beat in *Limax* exhibits $\mu = 11,500 \pm 250$. The ingestion of a small volume of sugar solution results in temporary change of μ to $16,200 \pm 320$, which accords quantitatively with the value obtained from these slugs in spring. This effect of the sugar is reversible, but lasts longer than the abolition of negative phototropism which the sugar also produces.

Other instances are given in which the value of the temperature characteristics for vital processes have been changed experimentally. The new values which appear have already been obtained in connection with homologous activities.

These results confirm the view that the critical thermal increments serve to characterize recognizably different governing reactions in living matter, and indicate a basis for specific experimental control.

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